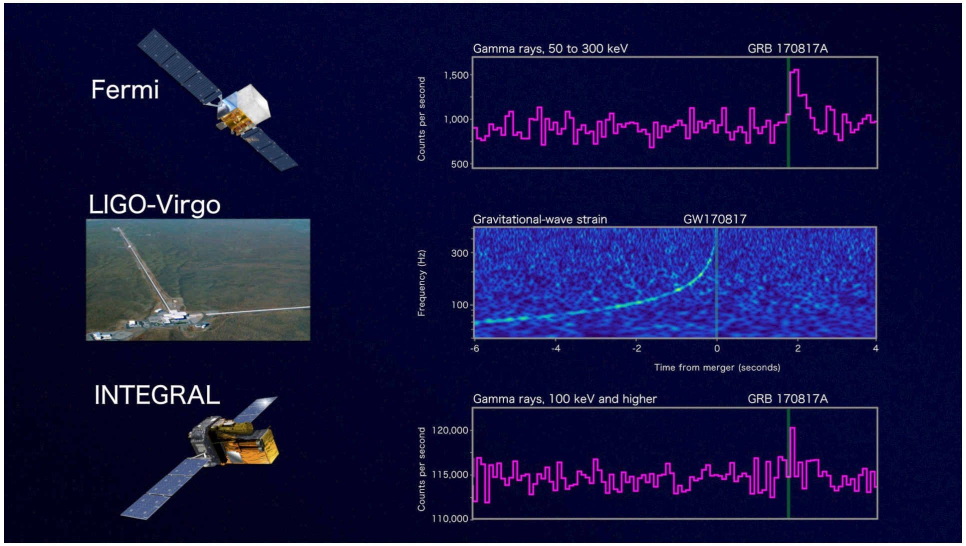
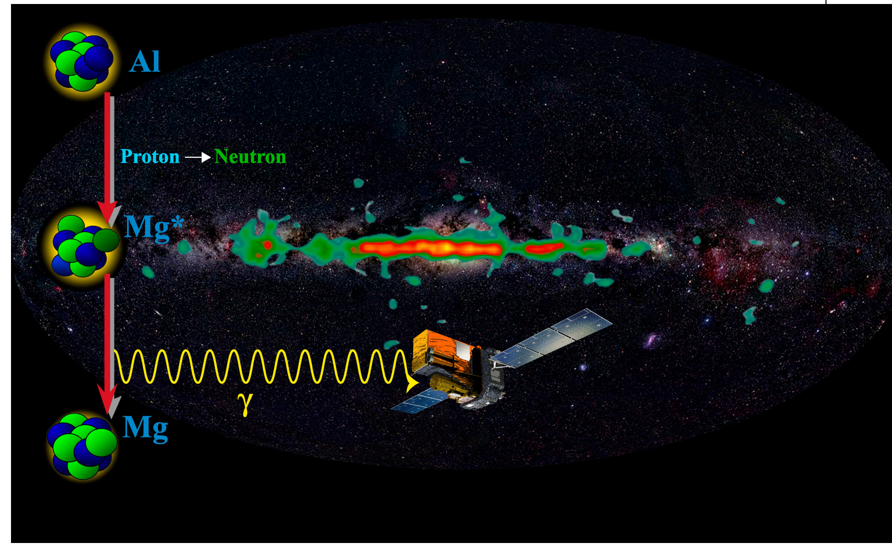
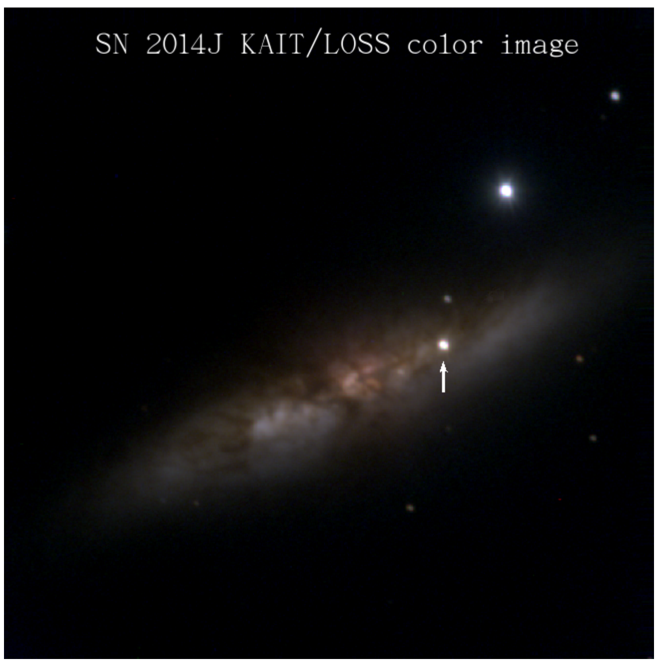
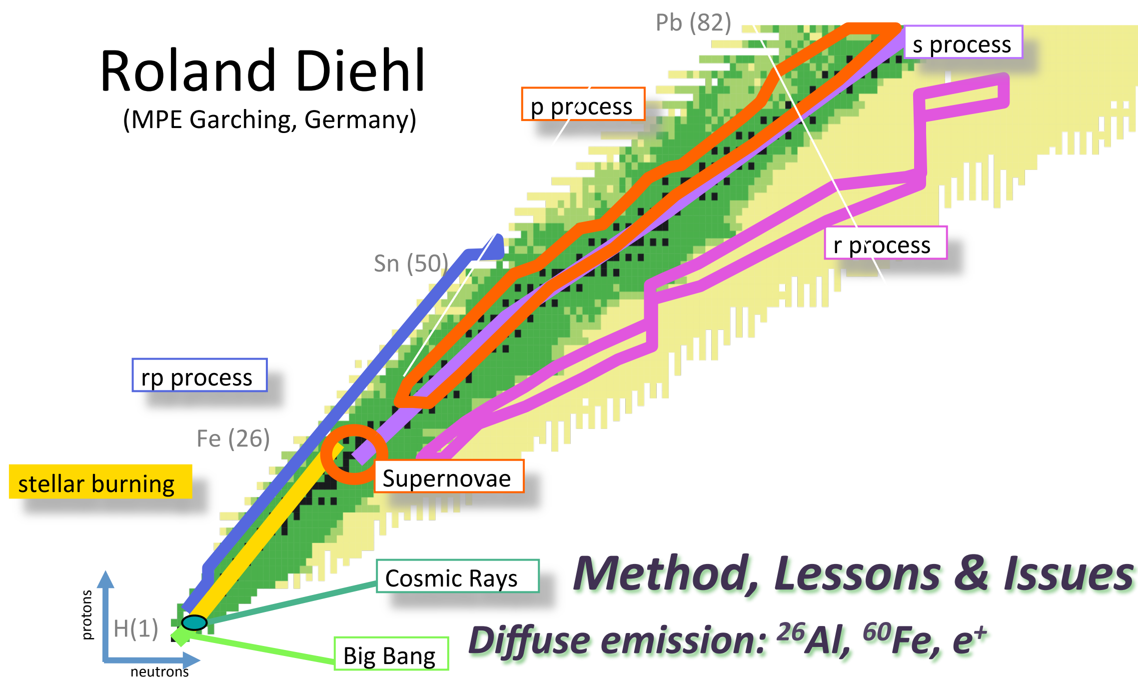
Learning from cosmic gamma-ray observations









Roland Diehl
(MPE Garching, Germany)

Method, Lessons & Issues

Diffuse emission: ^{26}Al, ^{60}Fe, e^+

Specific sources: Supernovae Ia, CC

Current Nuclear Gamma-Ray Line Telescopes

INTEGRAL

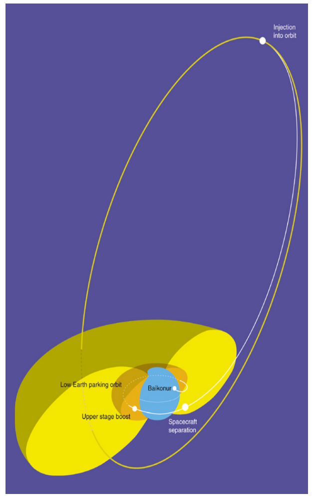
2002-(2019+..2029)

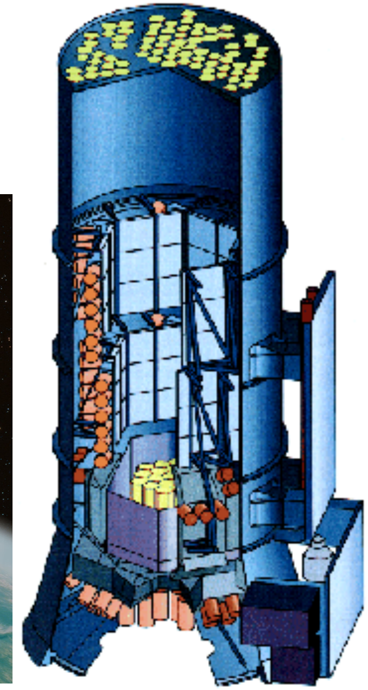
ESA

high E resolution

Ge detectors

15-8000 keV





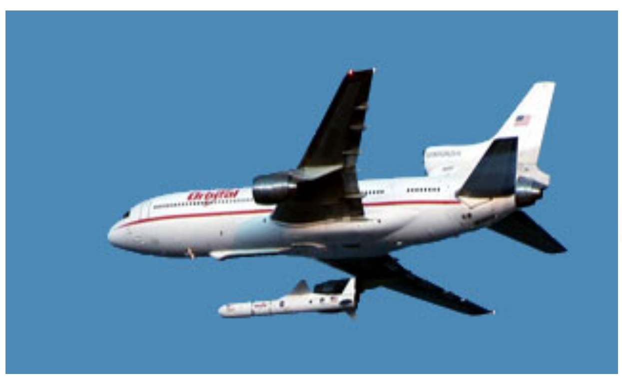
NuSTAR (<80 keV!)

2012-(2020+) …

NASA

hard X ray

imaging <80 keV



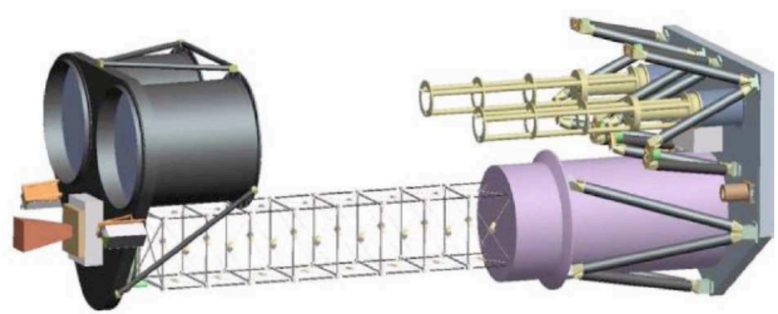
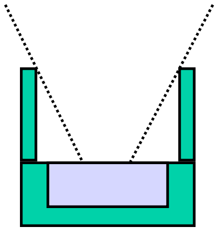
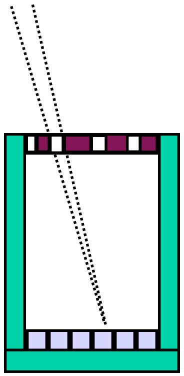


Fig. 1. NuSTAR telescopes in deployed configuration

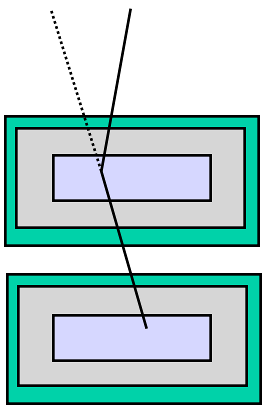
MeV Range Gamma-Ray Telescope Principles



- **Simple Detector (& Collimator)**
  (e.g. HEAO-C, SMM, CGRO-OSSE)
  Spatial Resolution (=Aperture) Defined Through Shield



- **Coded Mask & Detector Array**
  (e.g. SIGMA, INTEGRAL, SWIFT)
  Spatial Resolution Defined by Mask & Detector Elements Sizes

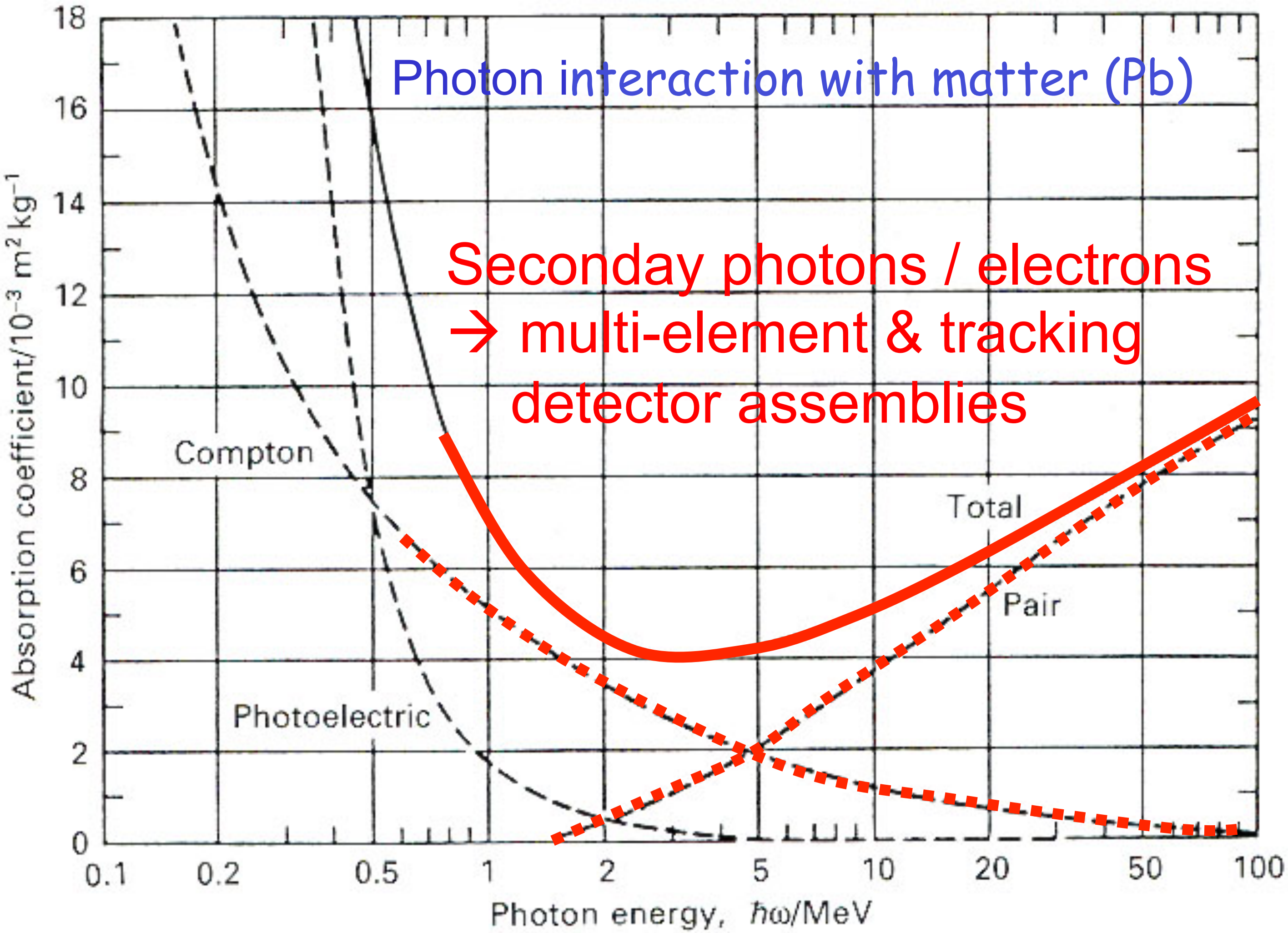


- **Compton Telescopes**
  (Coincidence-Setup of Position-Sensitive Detectors)
  (e.g. CGRO-COMPTEL, GRIPS, ACT, ASTROGAM...)
  Spatial Resolution Defined by Detectors' Spatial Resolution

Achievable Sensitivity: ~10^{-5} ph cm^{-2} s^{-1}, Angular Resolution ~ deg

Gamma-Ray Astronomical Telescopes:

Interaction of high-energy photons with matter

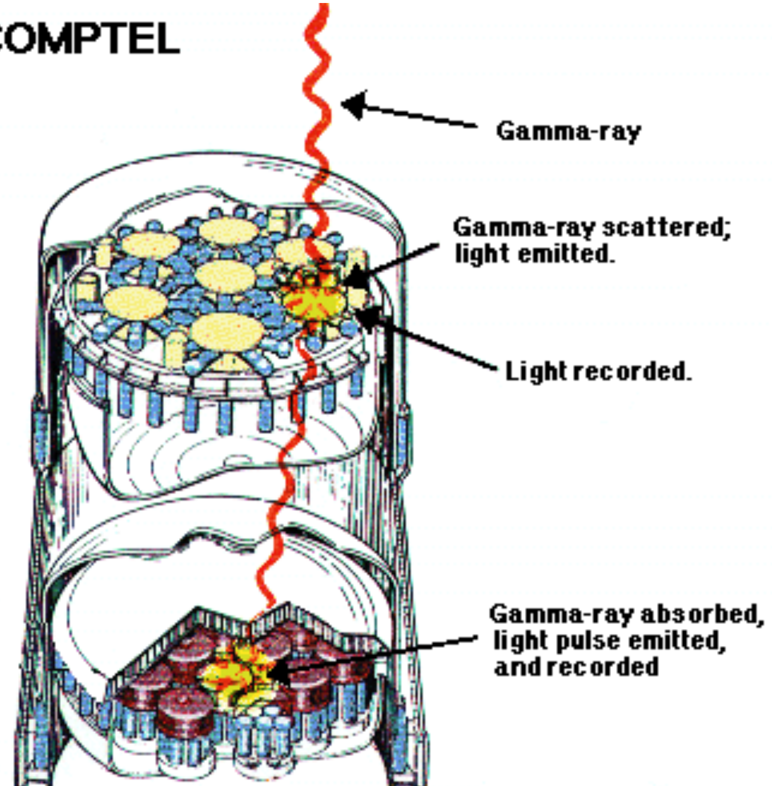


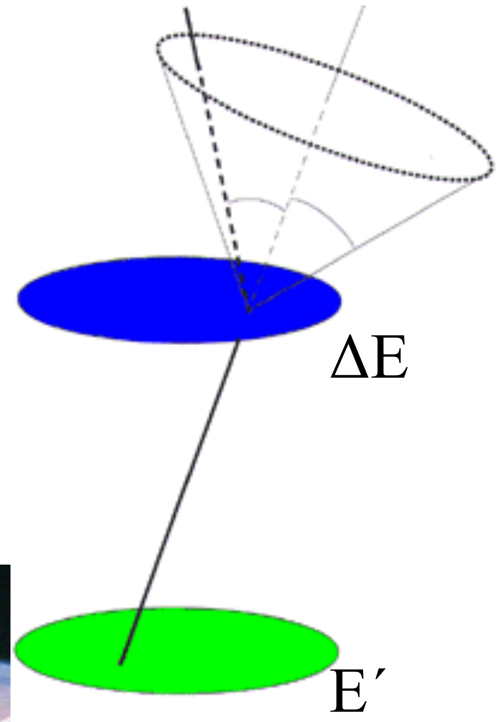
→ Secondary Particles … → e.m. cascade

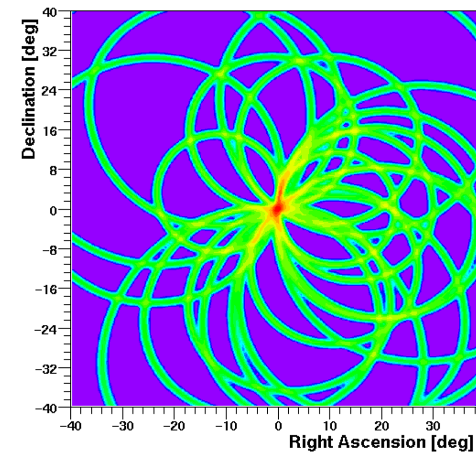
Compton Telescope

Compton scattering → a coincidence technique

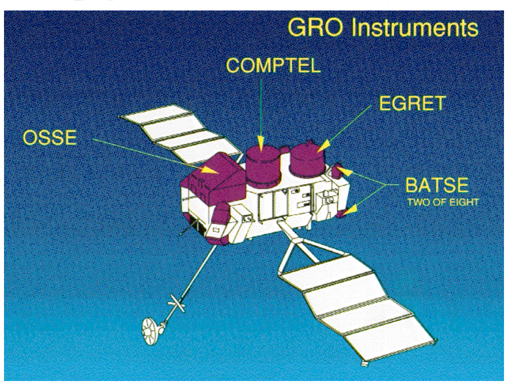
COMPTEL







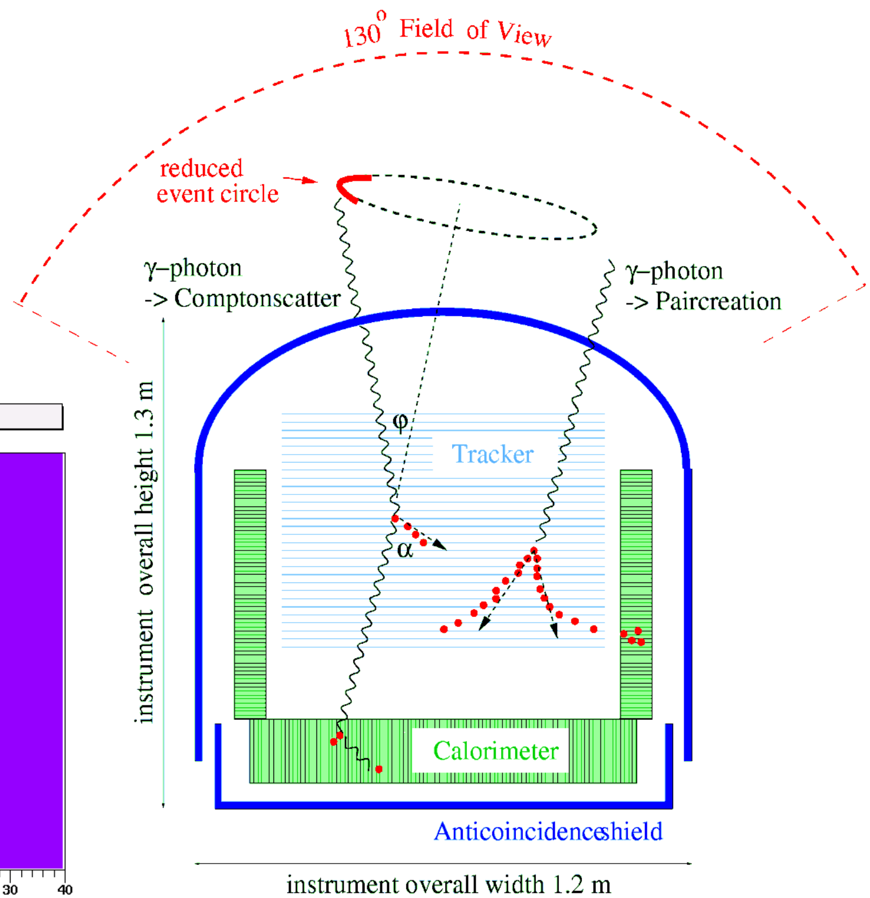
$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$



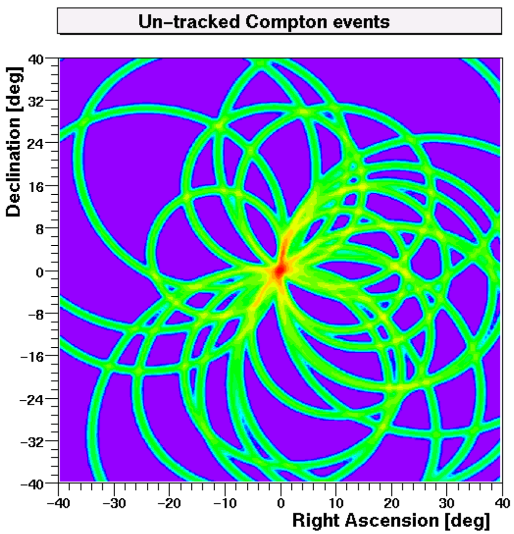
$$\varphi_{geometric} = \arccos\left\{1 + m_e c^2\left(\frac{1}{E_\gamma} - \frac{1}{E_\gamma - \Delta E}\right)\right\}$$

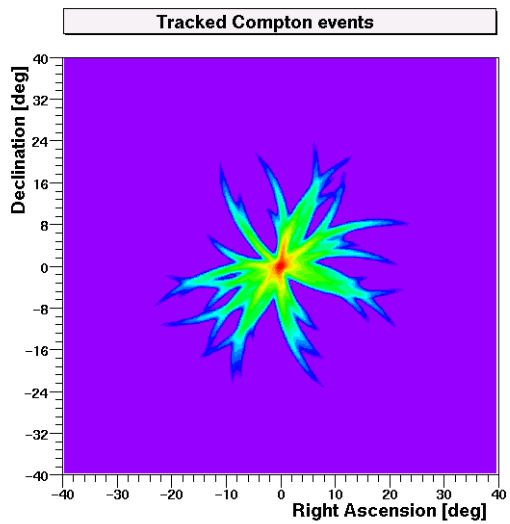
Measure Compton scattering and pair processes

- ☆ Measure all interactions that derive from an incident photon
  - ☞ Improvement as Direction (momentum) of secondary electron is measured in a tracker



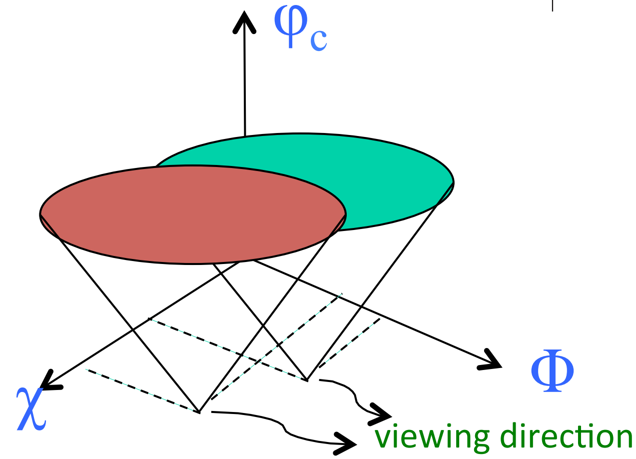
- ☆ 'event circle' skymaps:





Analysing COMPTEL Data

- Poissonian Statistics of Event Measurements
  - ☆ Incorporate expected statistical fluctuations
- Ambiguities for any E1, E2, X1, X2 set: different photon origins
  - ☆ Incorporate degeneracy of instrumental response

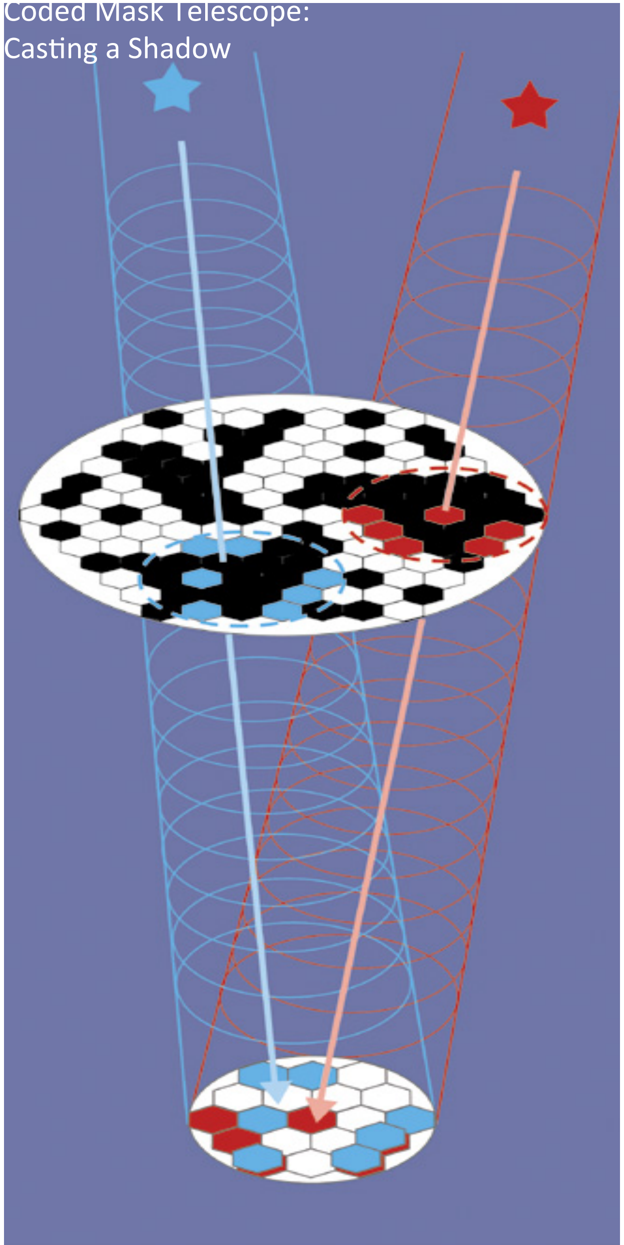


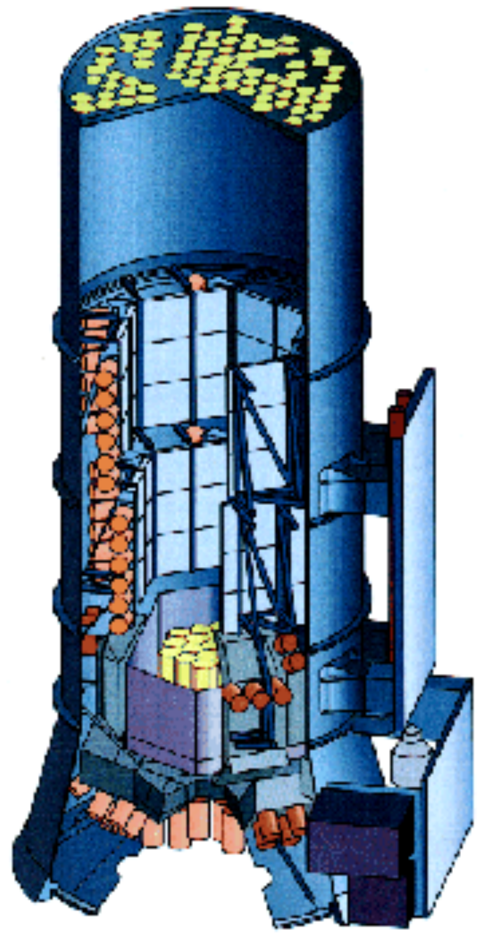
→ Iterative methods of improving a forward-folded model for data

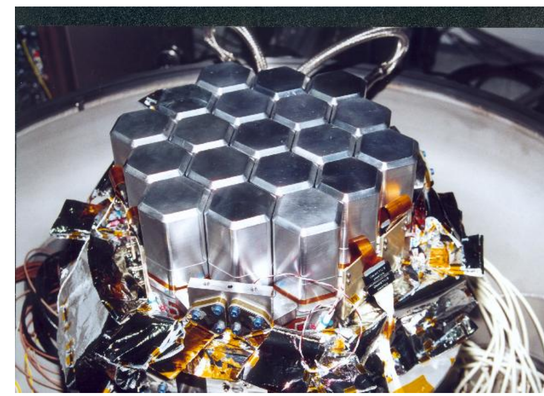
- Statistical de-convolution, or model fitting:
  - ☆ Likelihood of observing measured data, given a model
  - ☆ Discrepancy with real measurement used to improve model parameters
  - ☆ Improve model until "best fit" achieved / select best-fitting model

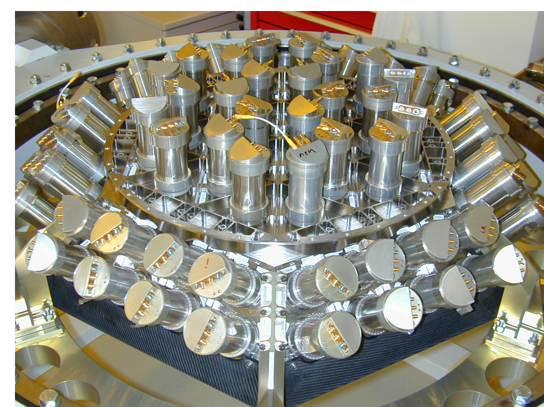
- Deconvolution results depend on model and fit/convergence method
  - ☆ Maximum Likelihood
  - ☆ Maximum Entropy
  - ☆ ...

Photon Measurements with a ‘coded mask’: The SPI Ge γ-Spectrometer









On INTEGRAL Spacecraft of ESA (2002)

Energy Range 15-8000 keV

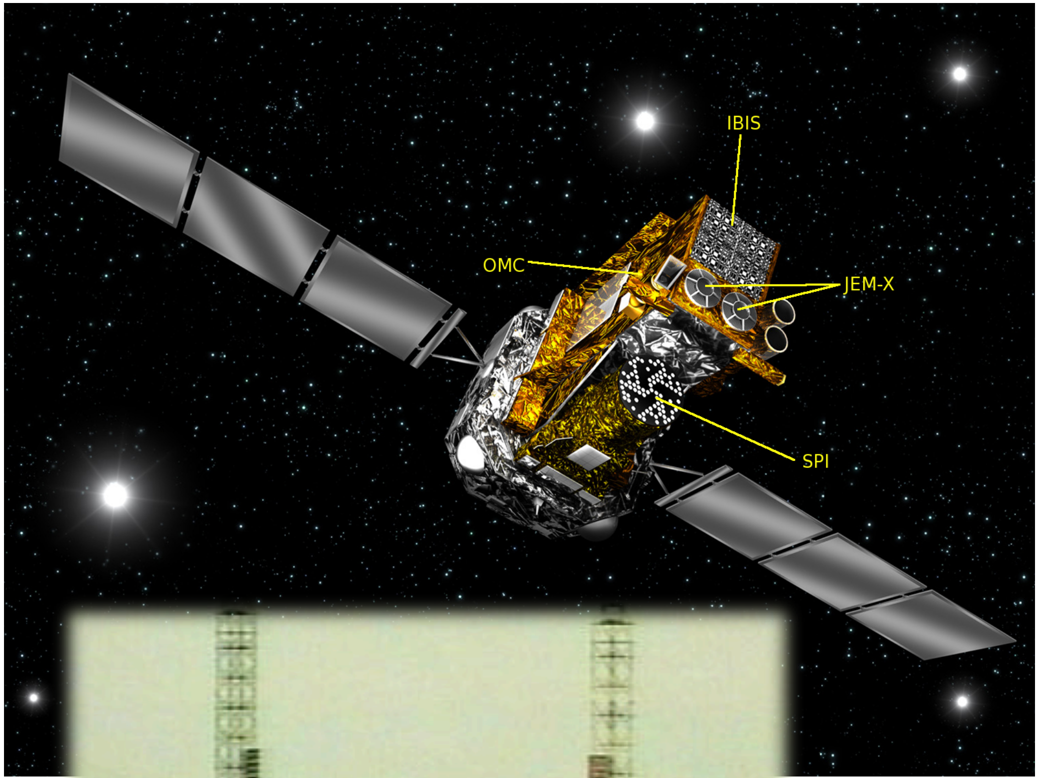
Energy Resolution ~2.2 keV @ 662 keV

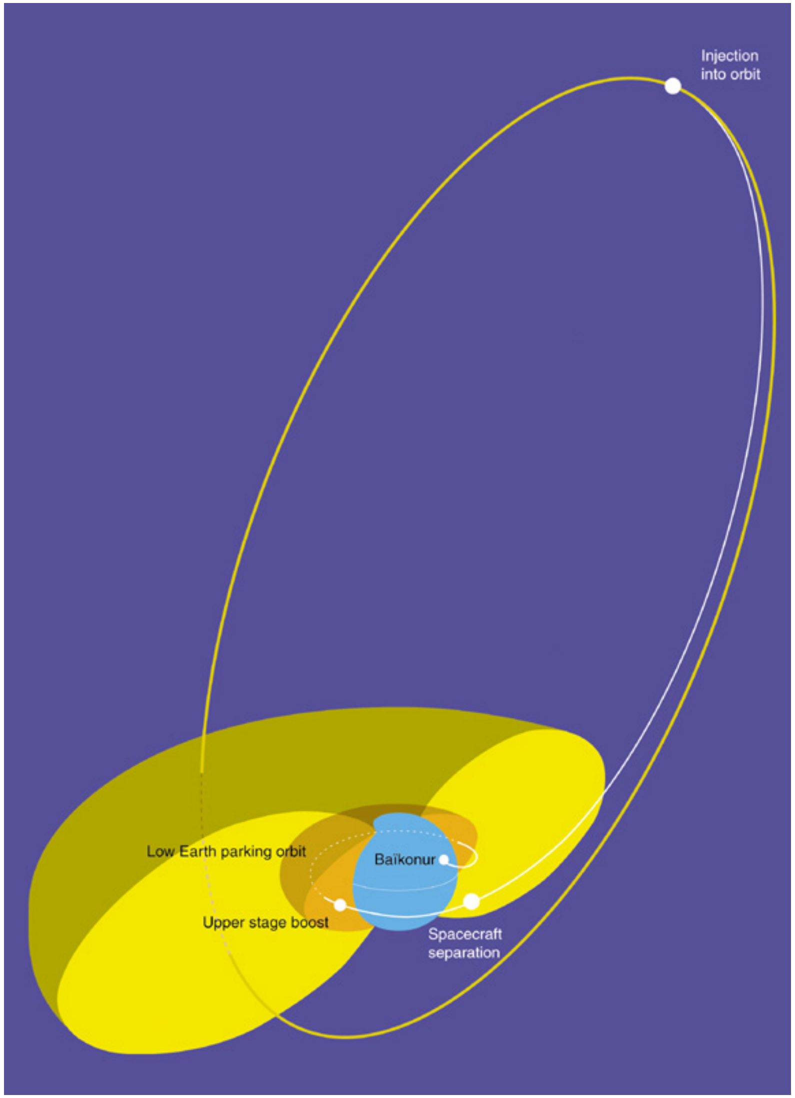
Spatial Precision 2.6^{o} / ~2 arcmin

Field-of-View 16x16^{o}

ESA's INTEGRAL Mission

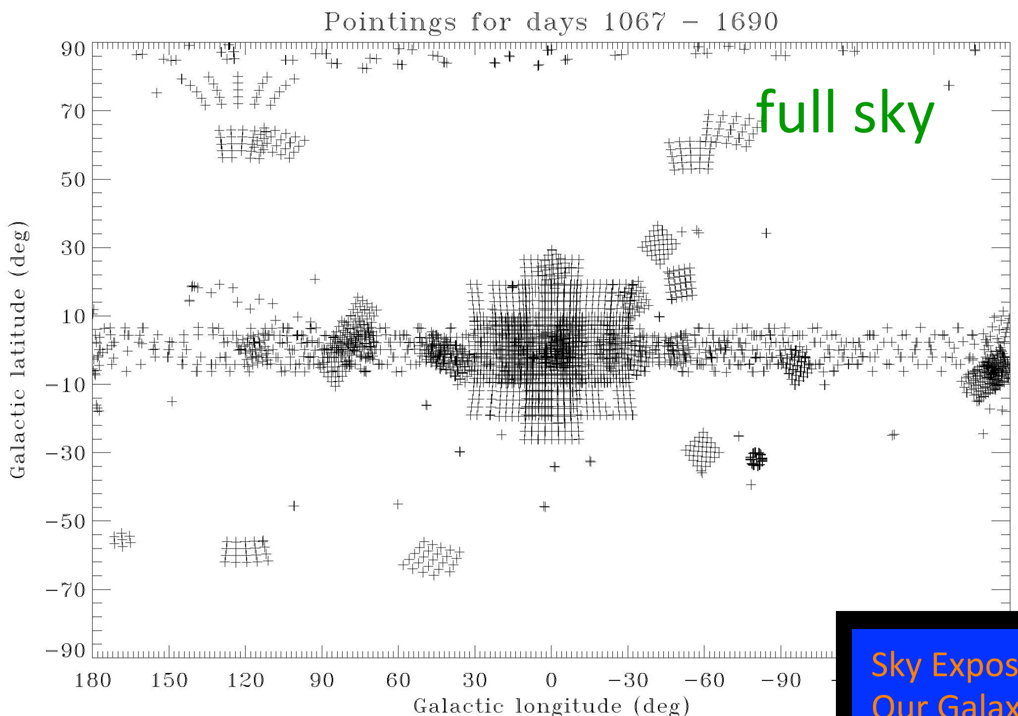
- Excentric 3-day orbit well above radiation belts → stable bgd
- Launched 2002 for 3+2 years; extended after ESA bi-annual reviews; de-orbit in 2029



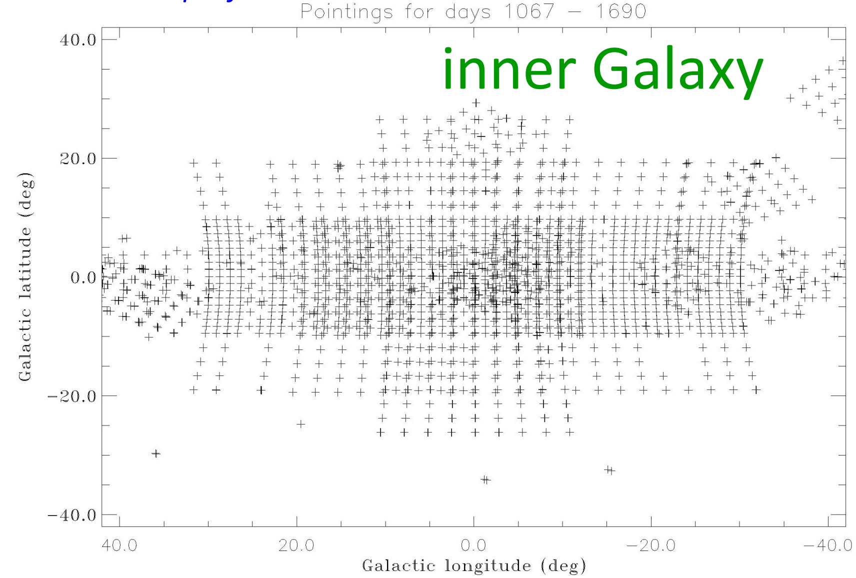


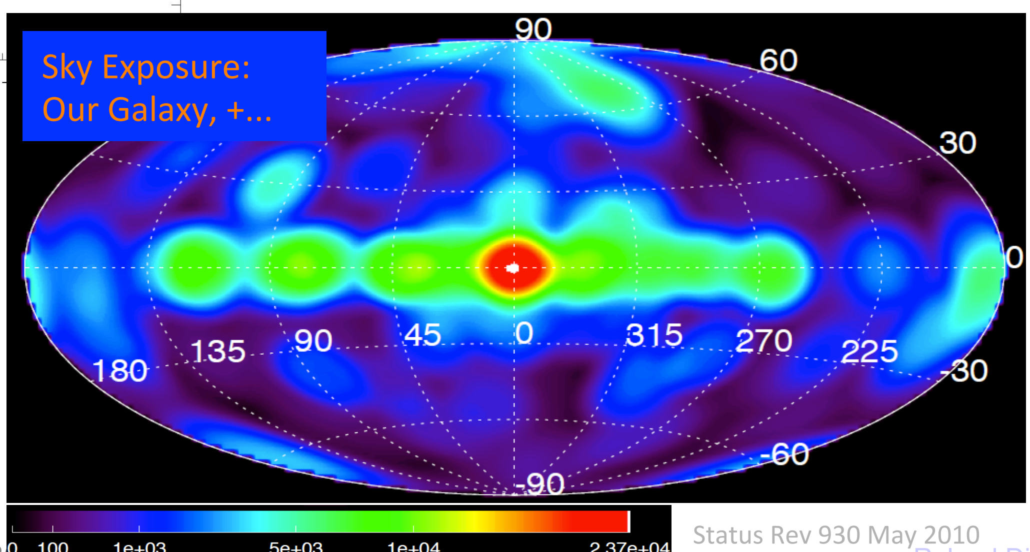
A Sky Survey with INTEGRAL

☆ "Dither Patterns" Scattered over the Sky



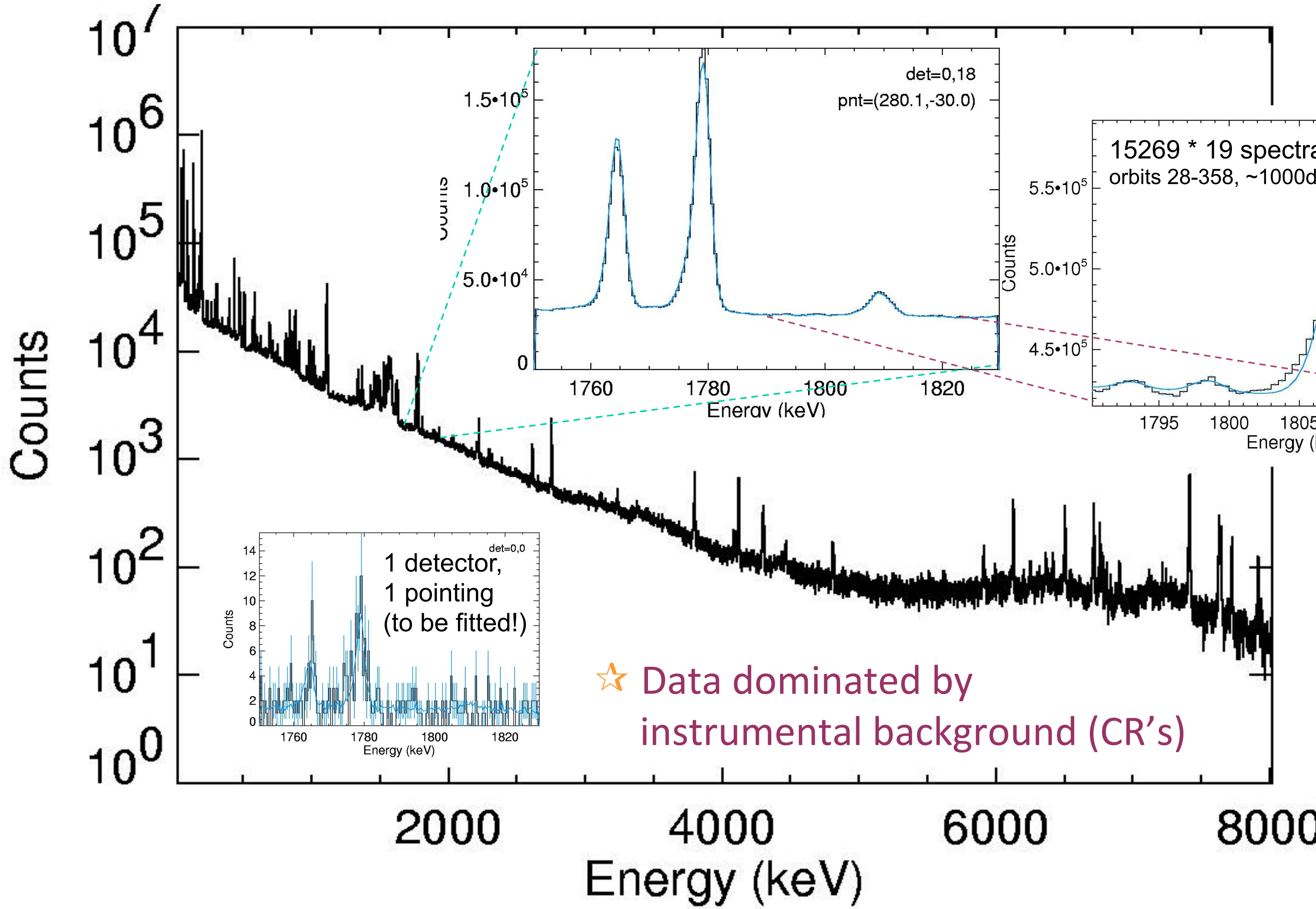
☞ *Example from late 2004*





Status Rev 930 May 2010

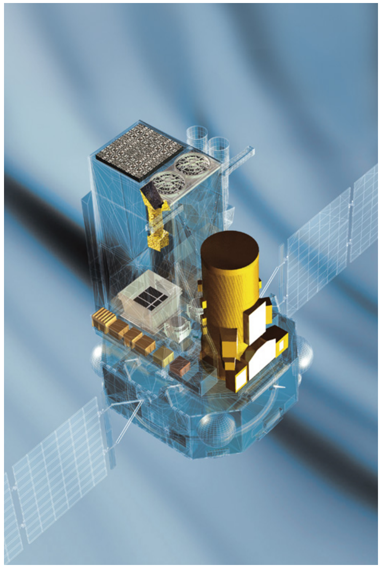
Energy Spectra: Characteristic Examples

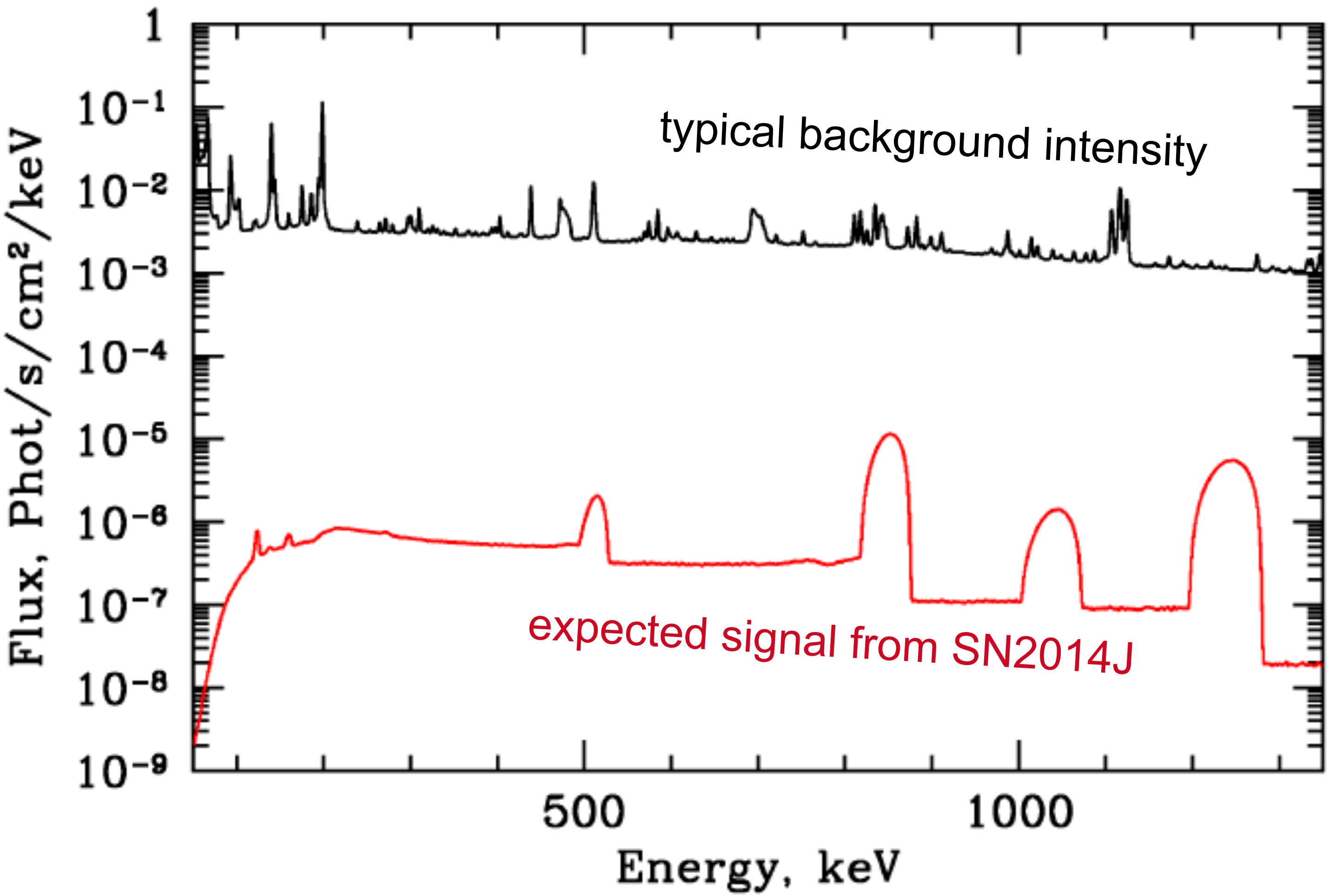


☆ Data dominated by instrumental background (CR's)

The Challenge of Finding SN2014J Gamma-Rays

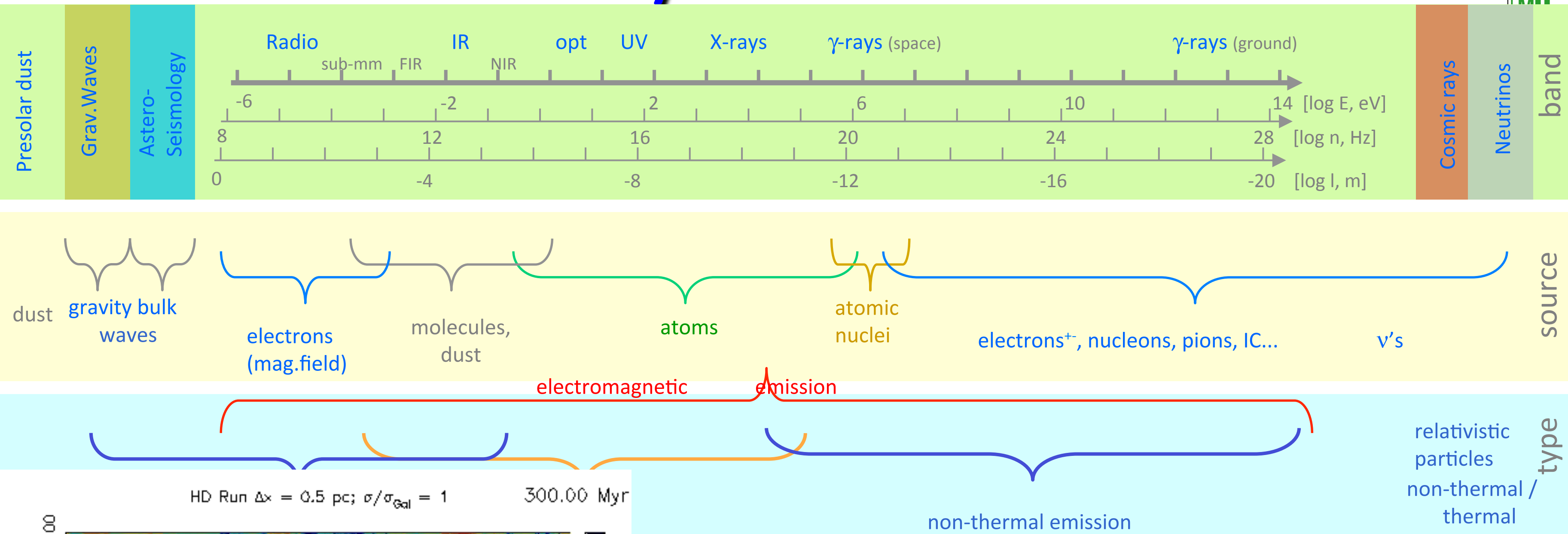
- ☆ Current Gamma-Ray Telescopes Have Large Intrinsic Background
  - Cosmic Ray Activation of Spacecraft and Instrument

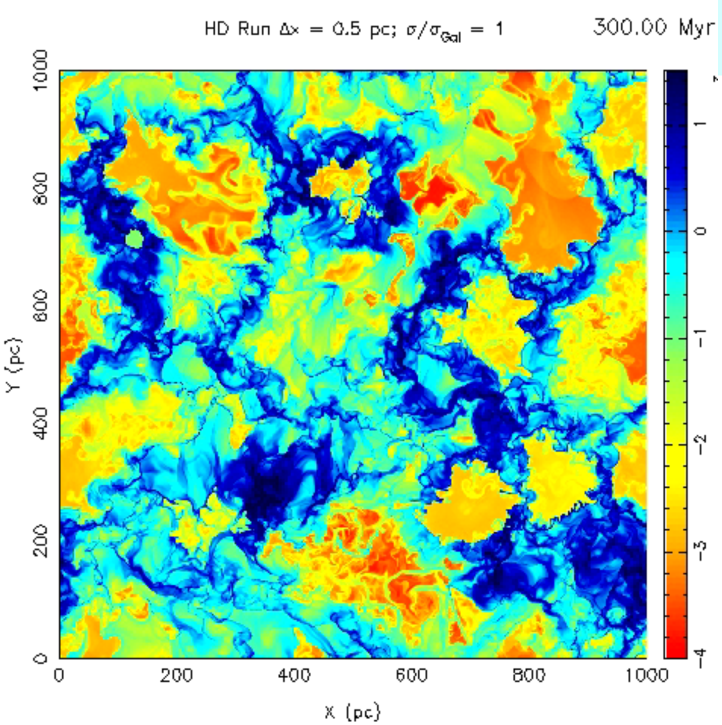




from Churazov et al., 2014

The variety of astronomies



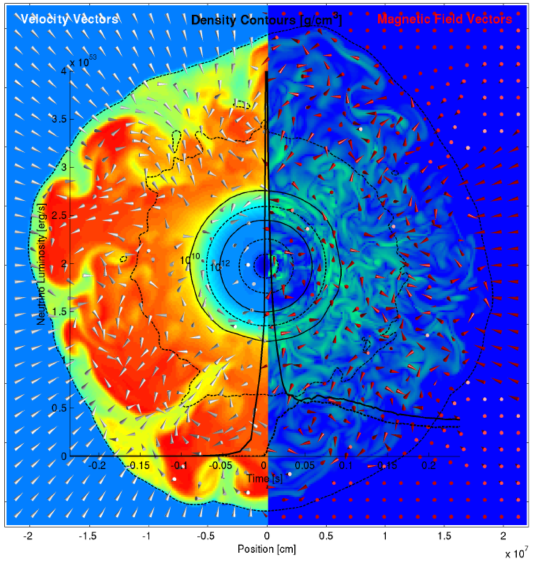


The variety of astrophysics

here:

stellar explosions

cosmic matter cycle



Nuclear Gamma-Ray Lines

Isotope	*Mean Lifetime*	*Decay Chain*	*γ -Ray Energy (keV)*
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^*+e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	85 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^*+e^+$	78, 68; 1157
^{26}Al	$1.04\ 10^6$y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	$3.8\ 10^6$y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332
e^+	.... 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

individual object/event

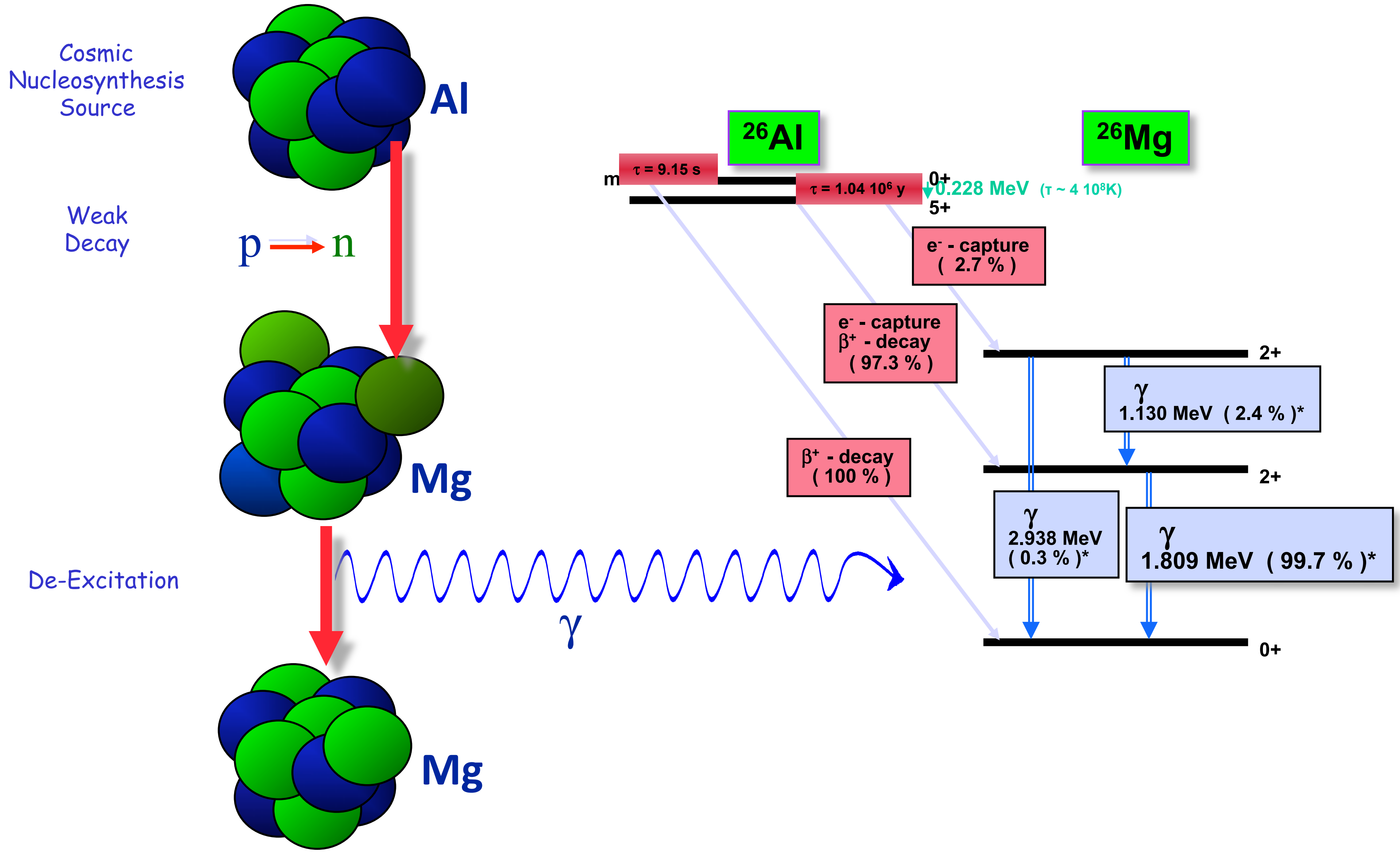
cumulative from many events

Radioactive trace isotopes are by-products of nucleosynthesis

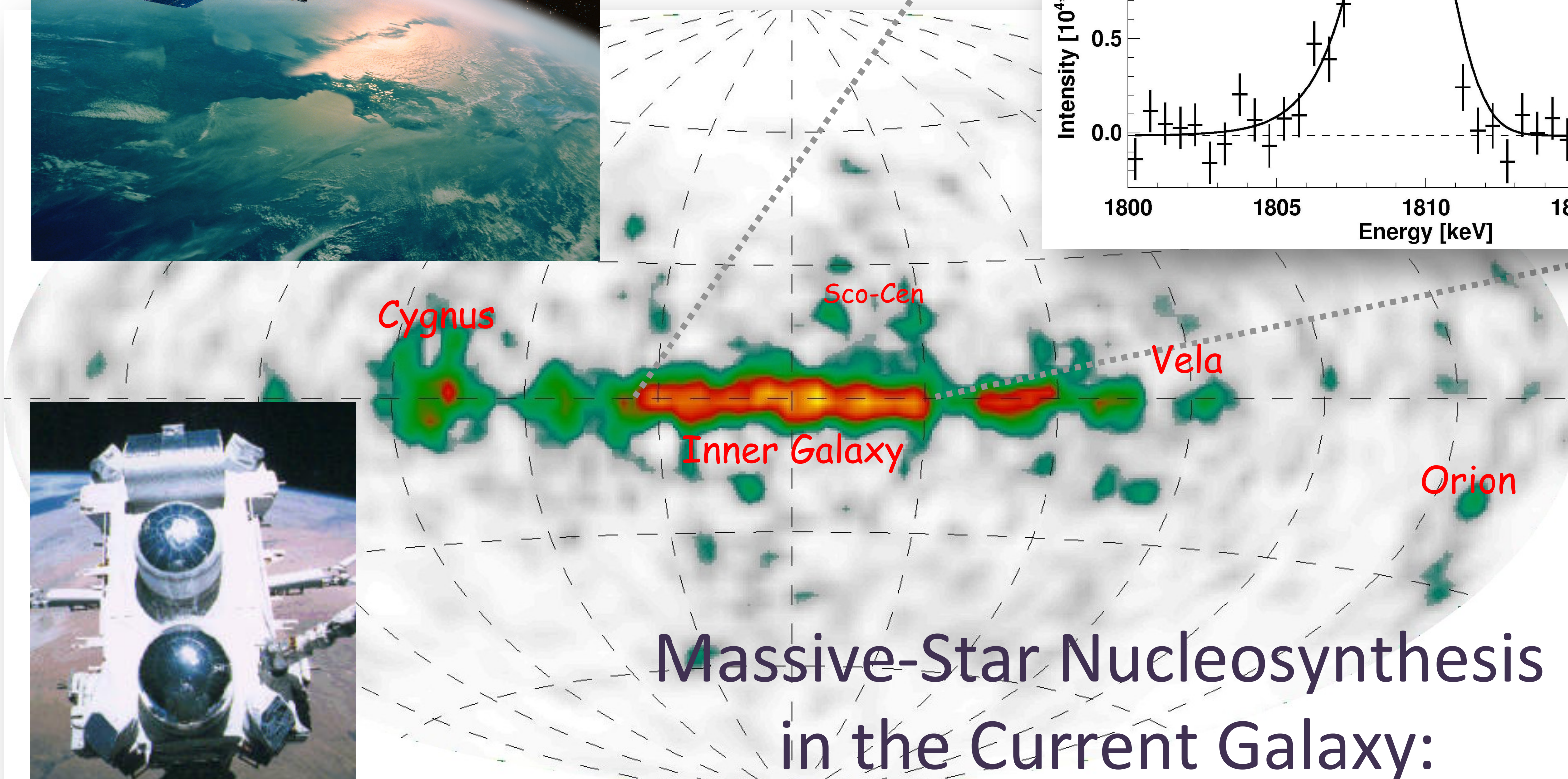
For gamma-ray detections we need:

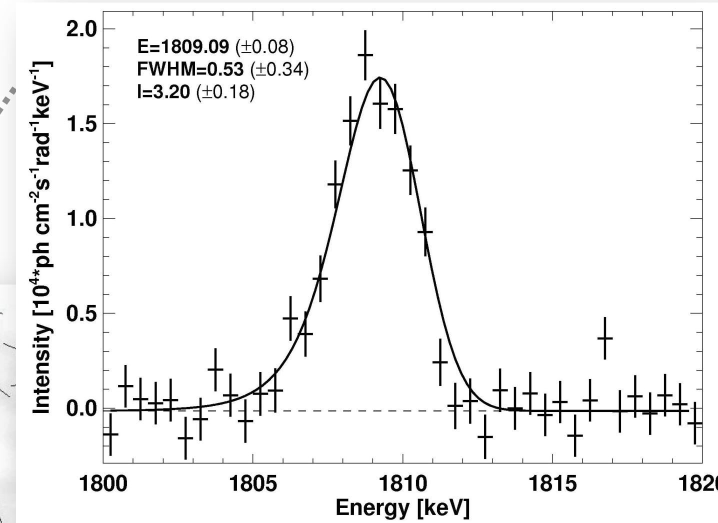
- Decay Time > Source Dilution Time (~weeks) (→ no < days lifetimes)
- Yields > Instrumental Sensitivities (10^{-5} ph cm^{-2} s^{-1}) (→ no elements > Fe)

Radioactive Tracer of Nucleosynthesis



^{26}Al in our Galaxy: γ-ray Image and Spectrum





Massive-Star Nucleosynthesis
in the Current Galaxy:
Current Enrichment (~My) from ^{26}Al γ-rays

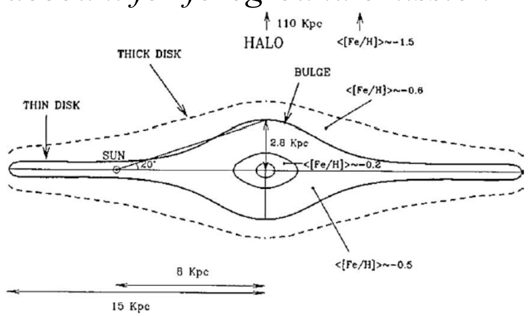
Using the ^{26}Al Line to Characterize the Galaxy's SN Activity

→ *Diehl et al., Nature 2006*
→ *Diehl et al., A&A 2010**
→ *Diehl et al., in prep. (2019)**

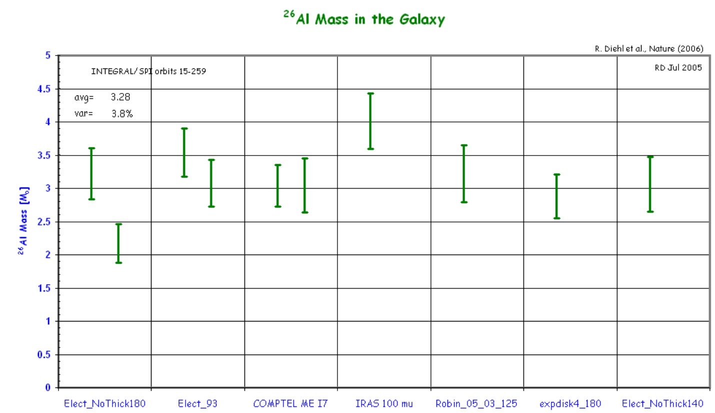
Measured Gamma-Ray Flux*

Galaxy Geometry

*) *better account for foreground emission*

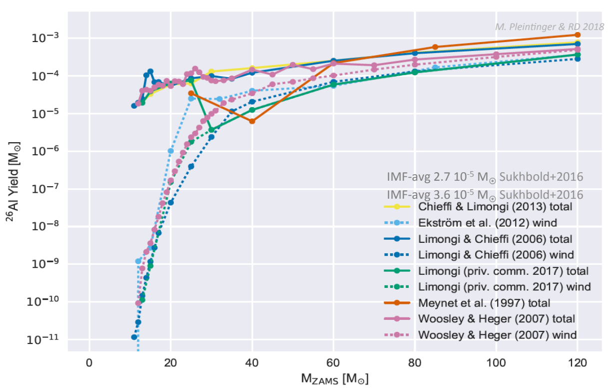


➢ ^{26}Al Mass in Galaxy = 2.0 (±0.3) $M_\odot$

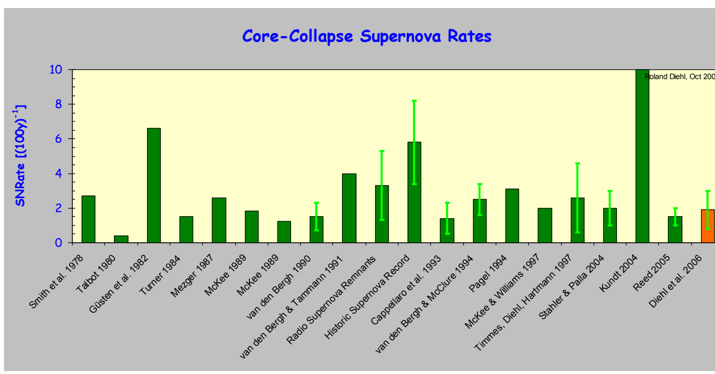


^{26}Al Yields per Star

Stellar Mass Distribution

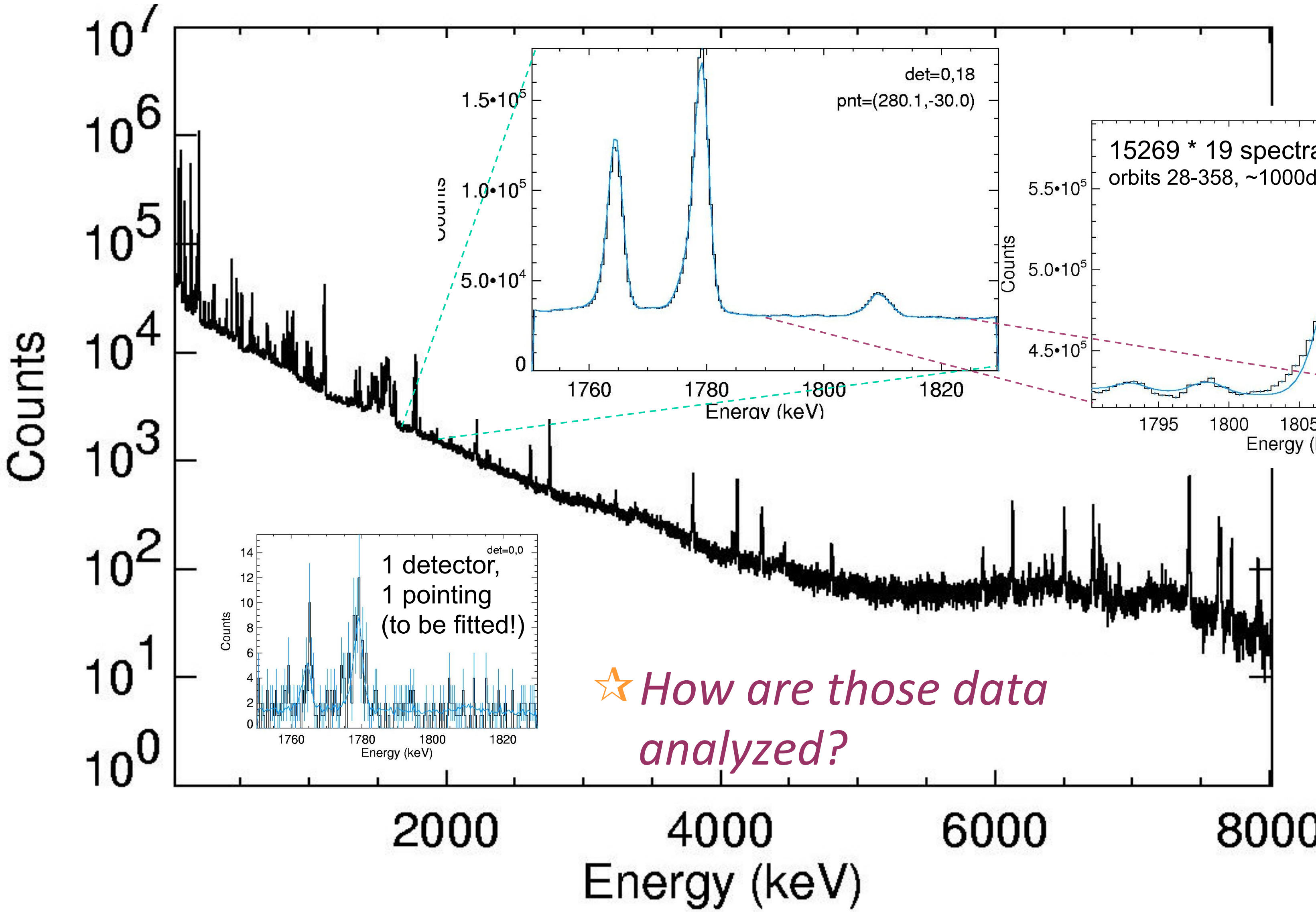


✓ cc-SN Rate = 1.3 (± 0.6) per Century



✓ Star Formation Rate = 2.8 $M_\odot$/yr

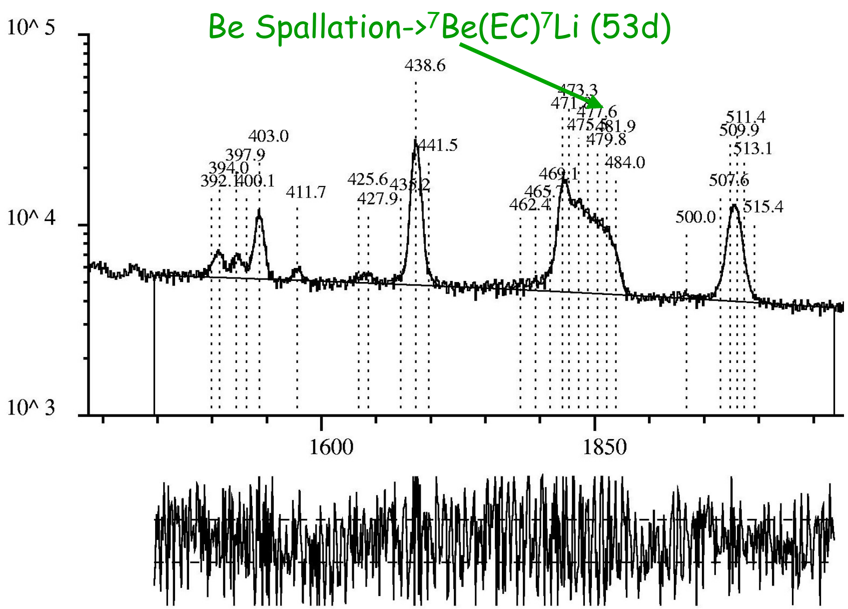
Energy Spectra: Characteristic Examples



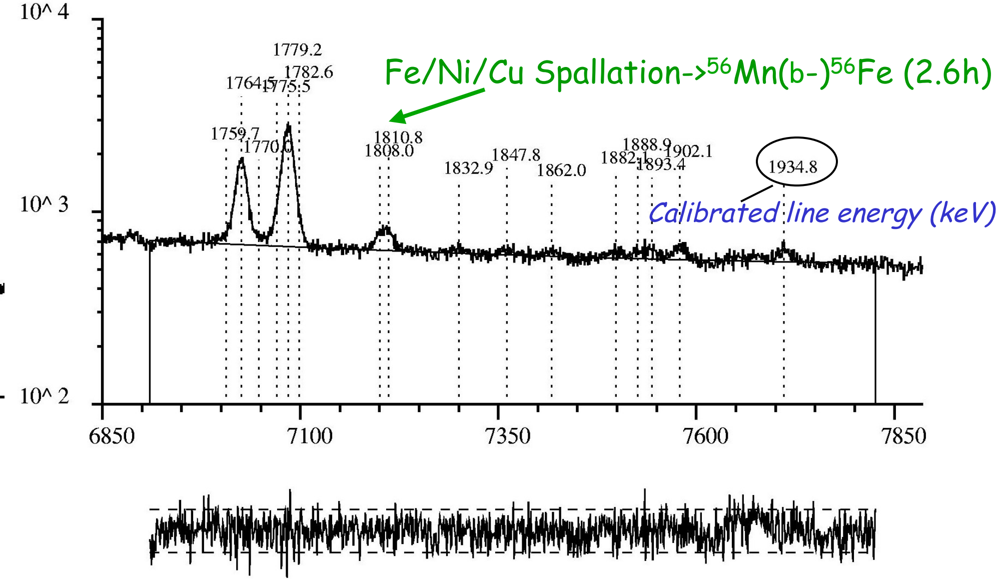
☆ *How are those data analyzed?*

Identification of Background Lines

… two examples…



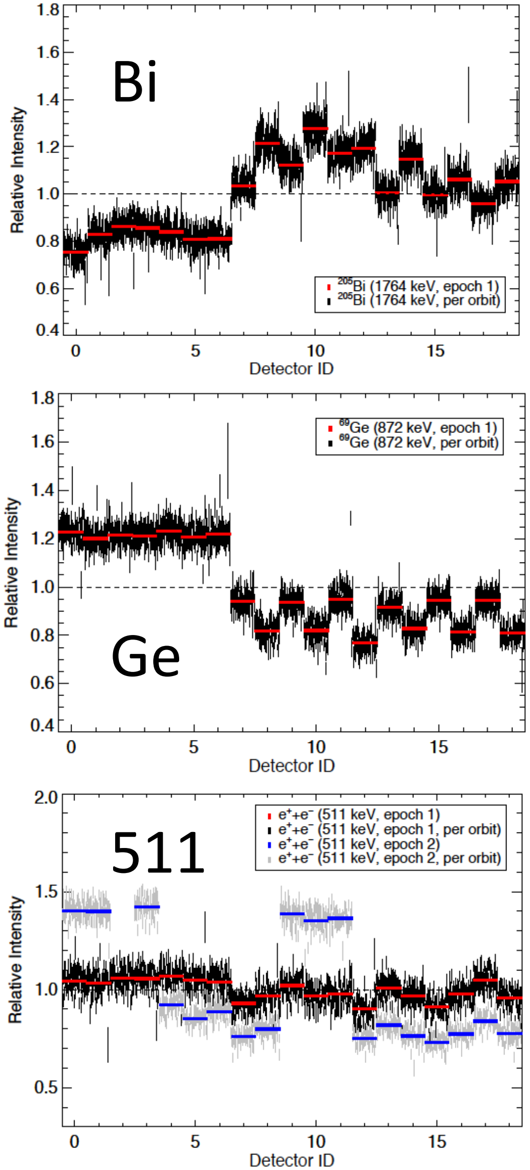
Cyg Obs Rev11

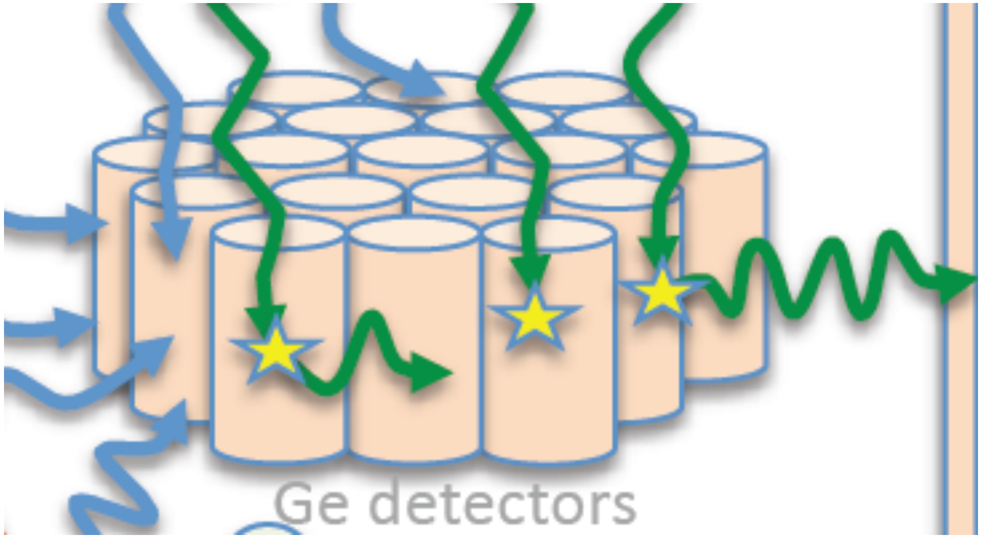


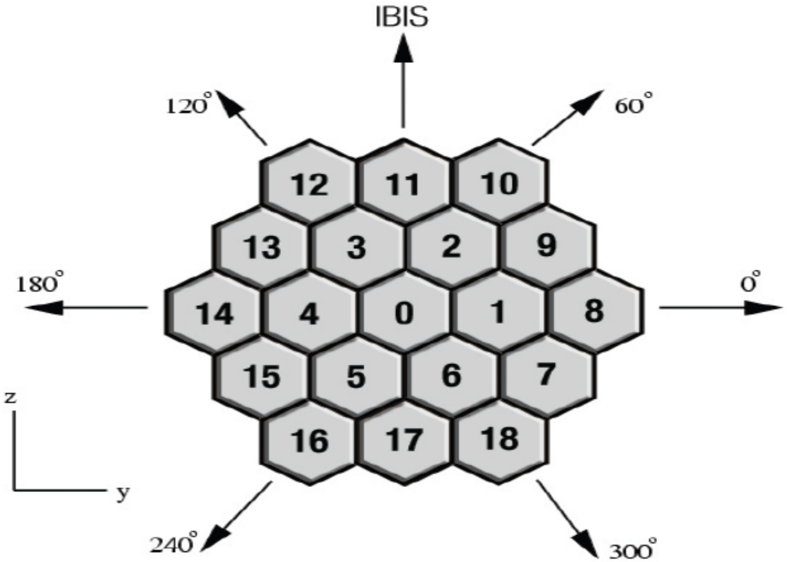
1. Detailed Spectral Fit with Instrumental Response -> Line Components
2. Isotope Identification per Line
   (Gamma-Ray Line Lists from 'Table-of-Isotopes' References

SPI instrumental background lines: remarks

- Lines show a characteristic intensity pattern in SPI Ge camera



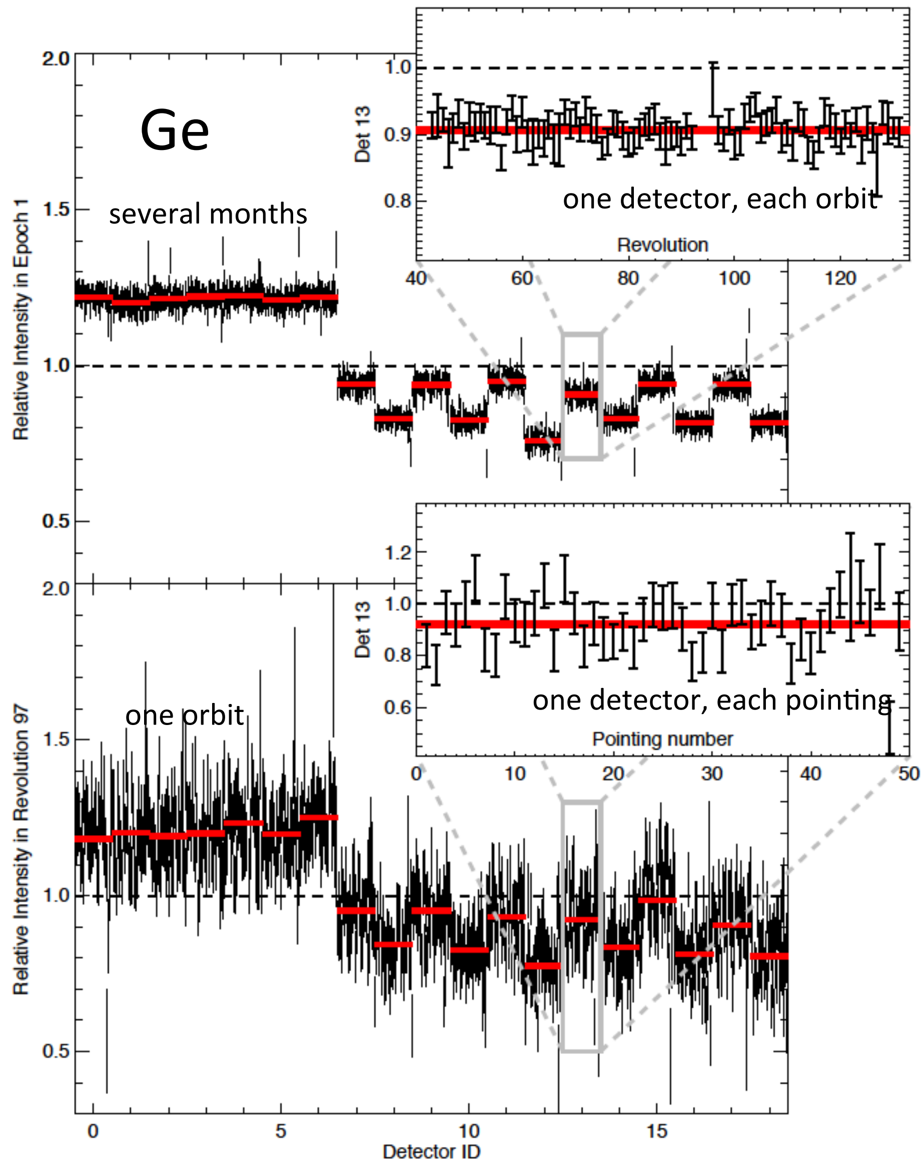




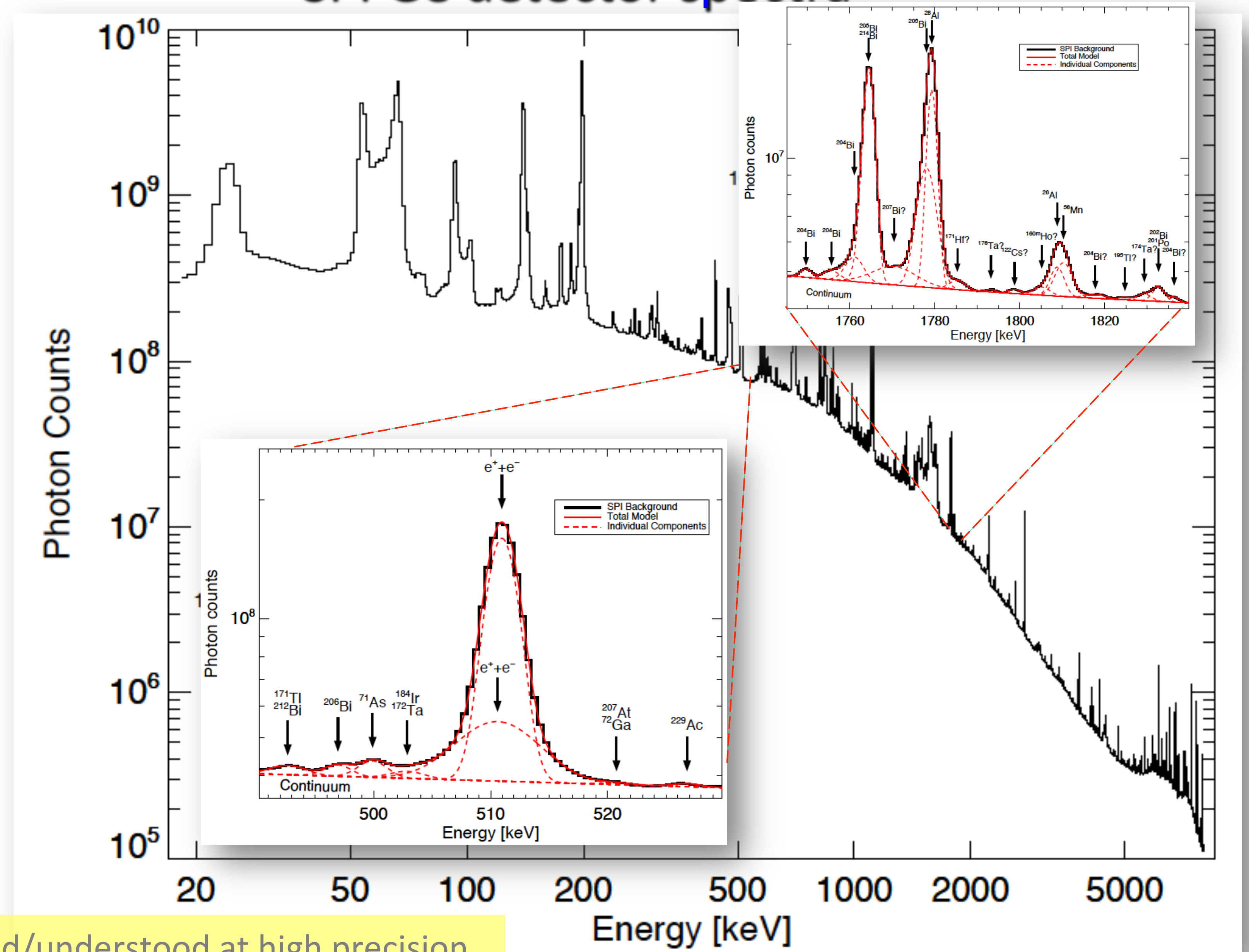
SPI instrumental background lines: remarks

Intensity patterns in camera are very stable over longer times:

the physical process (origin) remains the same



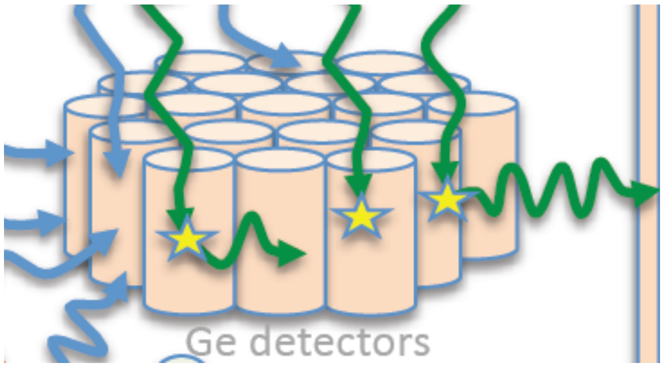
SPI Ge detector spectra

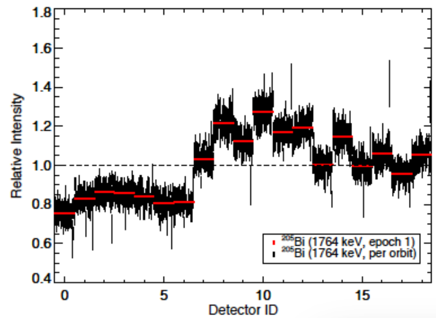


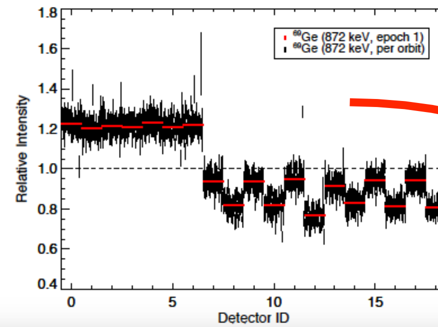
Modelled/understood at high precision

Discriminating Background and Sky Signals

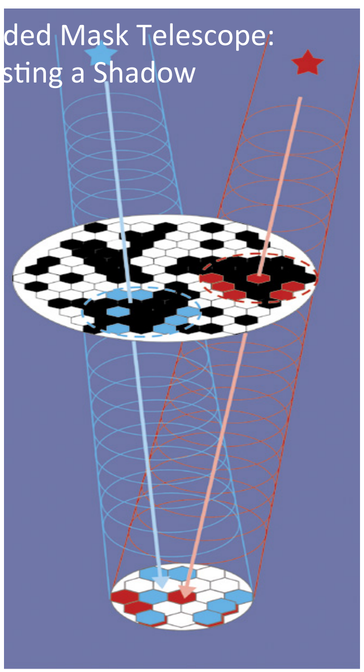
- Tracking the relative count rate ratios among detectors

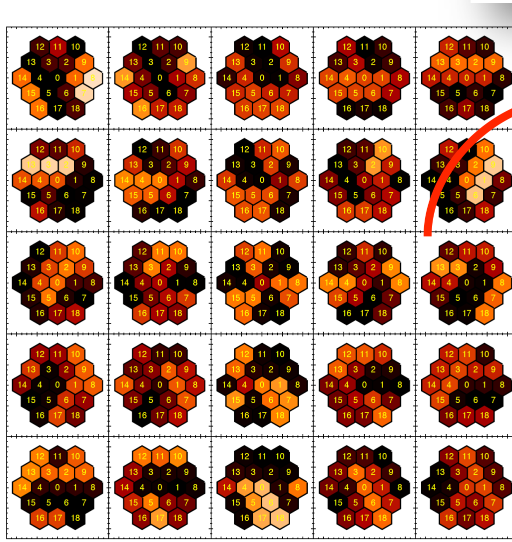


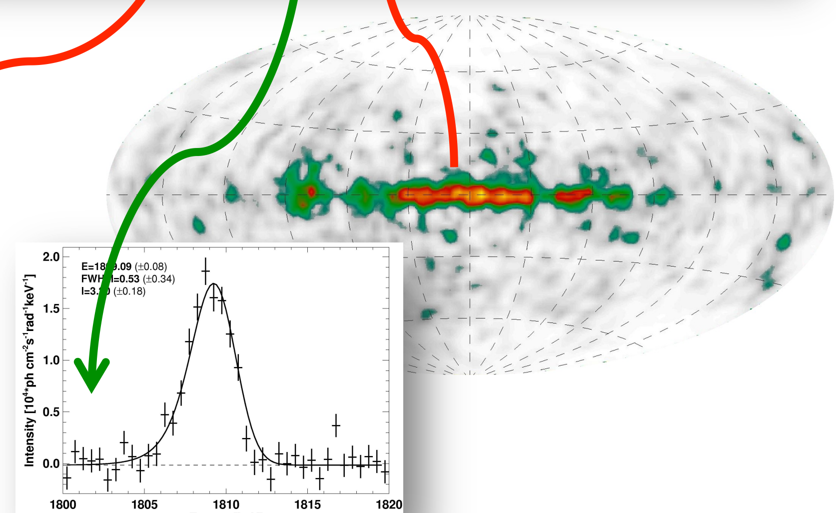




$$d_k = \sum_j R_{jk} \sum_{i=1}^{N_I} \theta_i M_{ij} + \sum_t \sum_{i=N_I+1}^{N_I+N_B} \theta_{i,t} B_{ik}$$



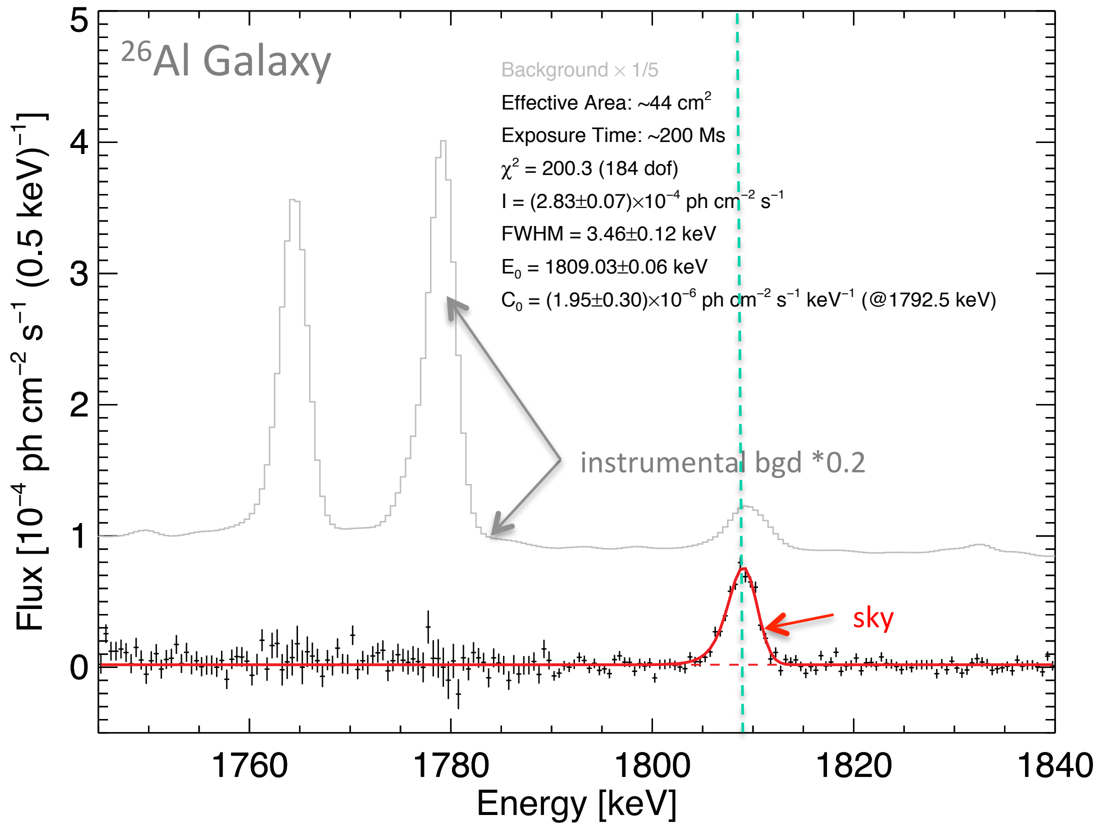


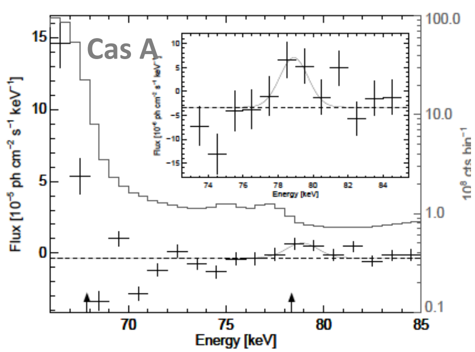


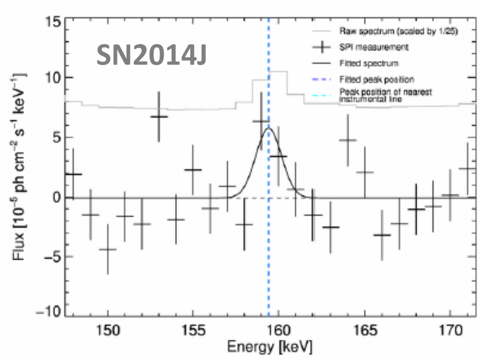
Gamma ray spectroscopy with SPI

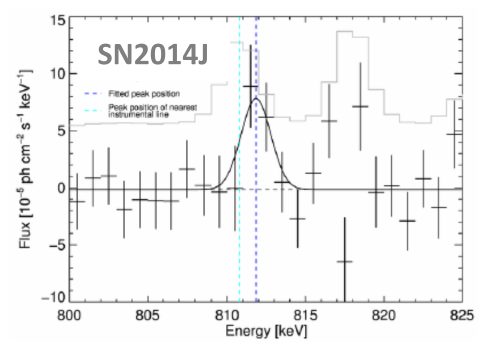
…it works!

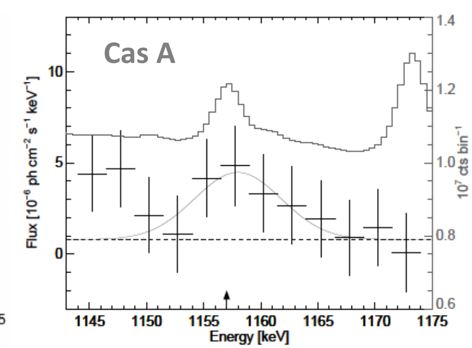
- ☆ ^{26}Al line 1808.6 keV
- ☆ instrumental lines
  - ☞ 1810 keV (!!)
  - ☞ 1779 keV
  - ☞ 1764 keV
- ☆ …also: SN ^{56}Ni, ^{44}Ti





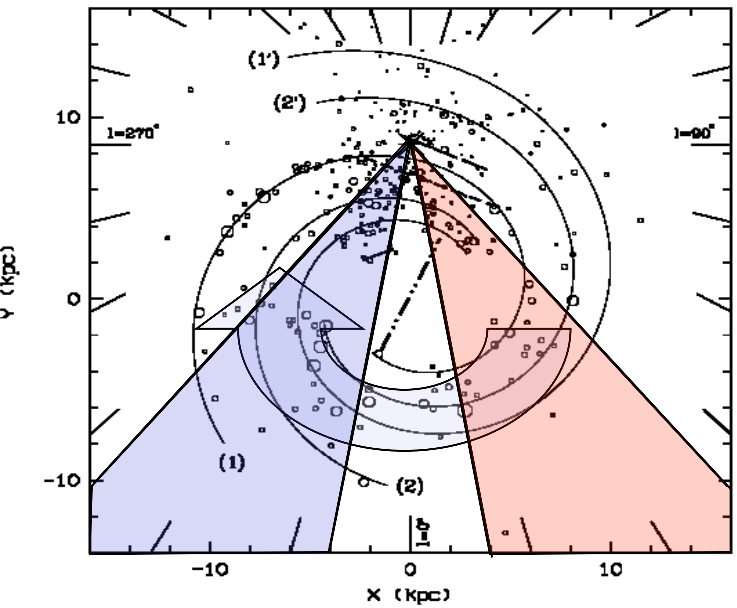


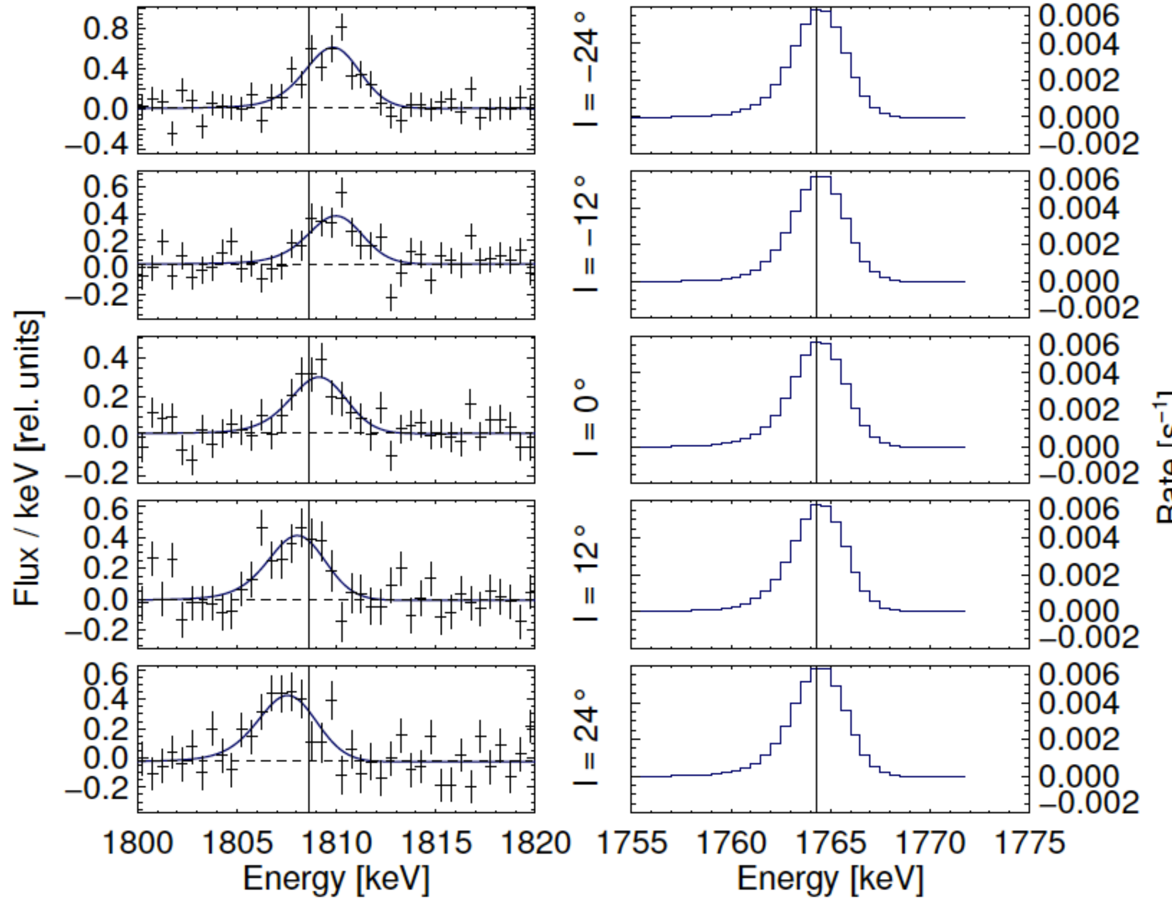




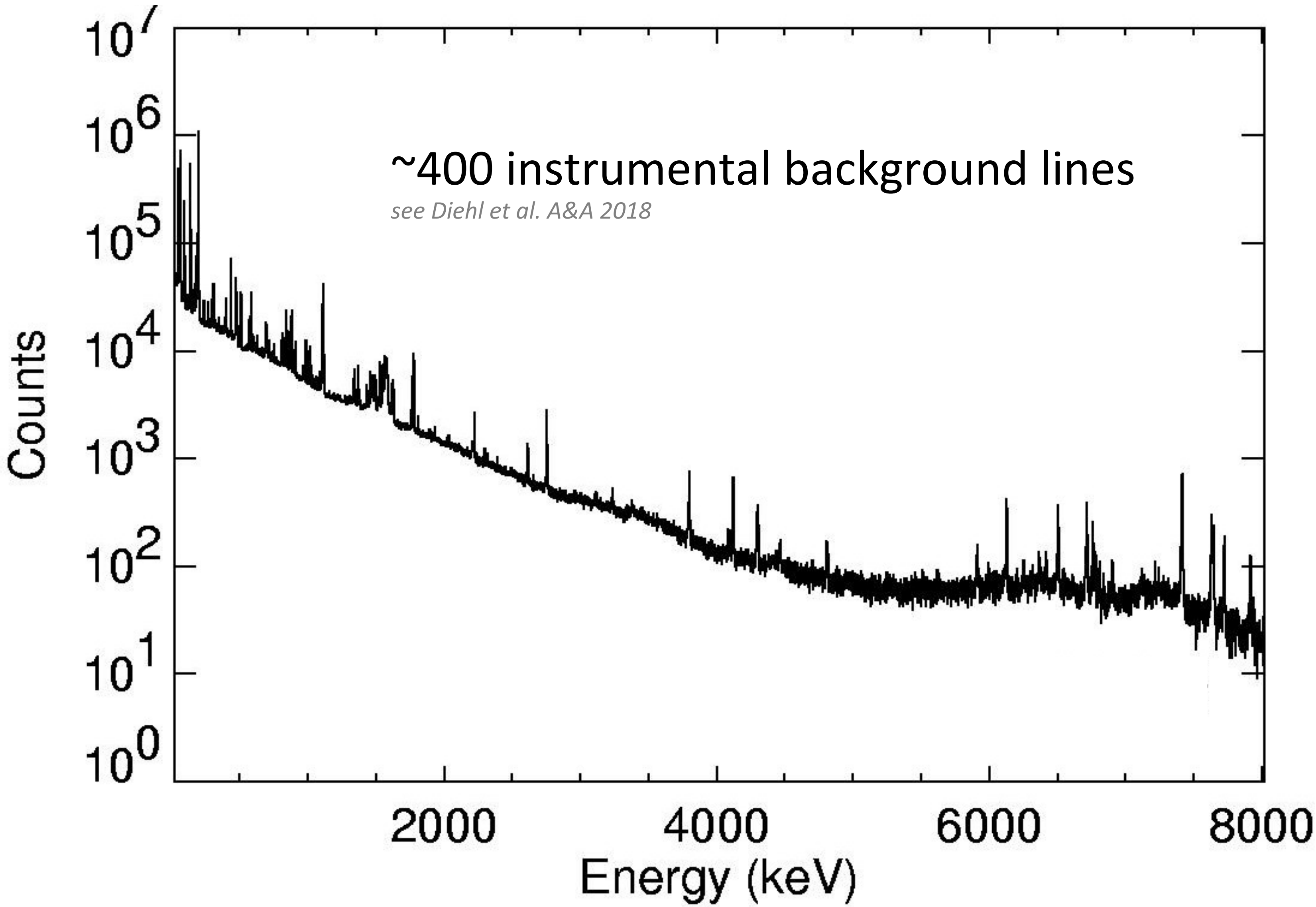
Spatially-Resolved Spectroscopy

- Analyze Line Shape and Position for Different Directions
  - ☆ Galactic Rotation

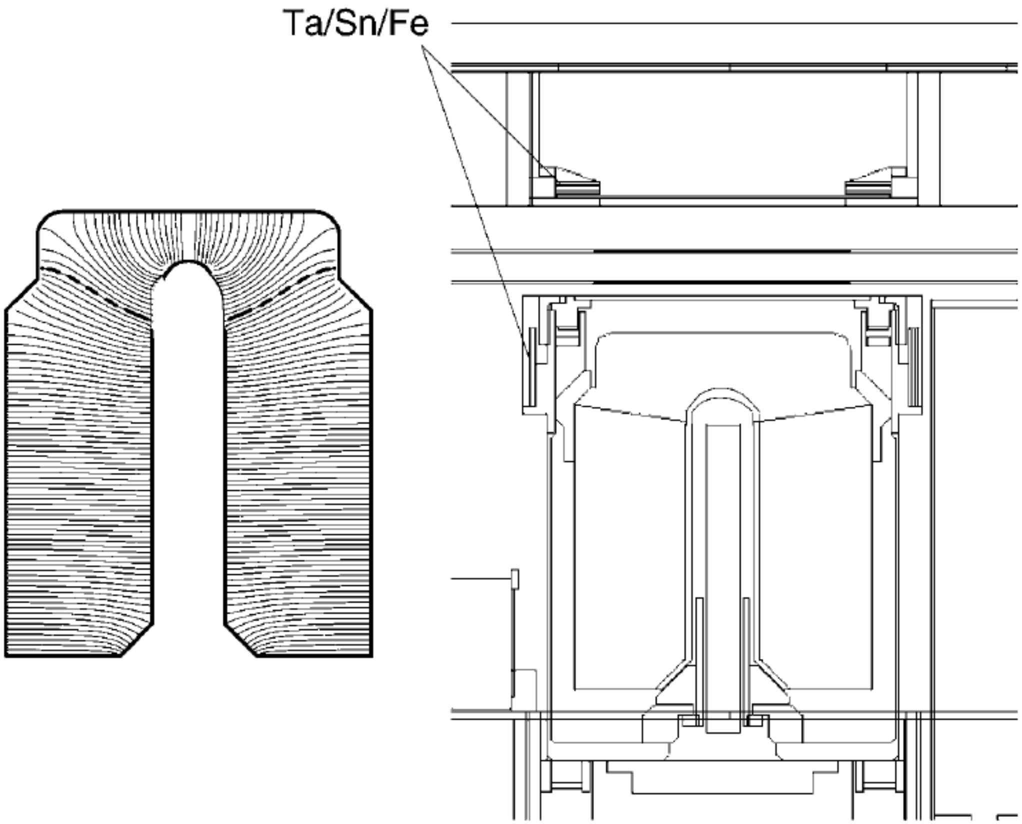




Characteristic Energy Spectra of SPI/INTEGRAL Data



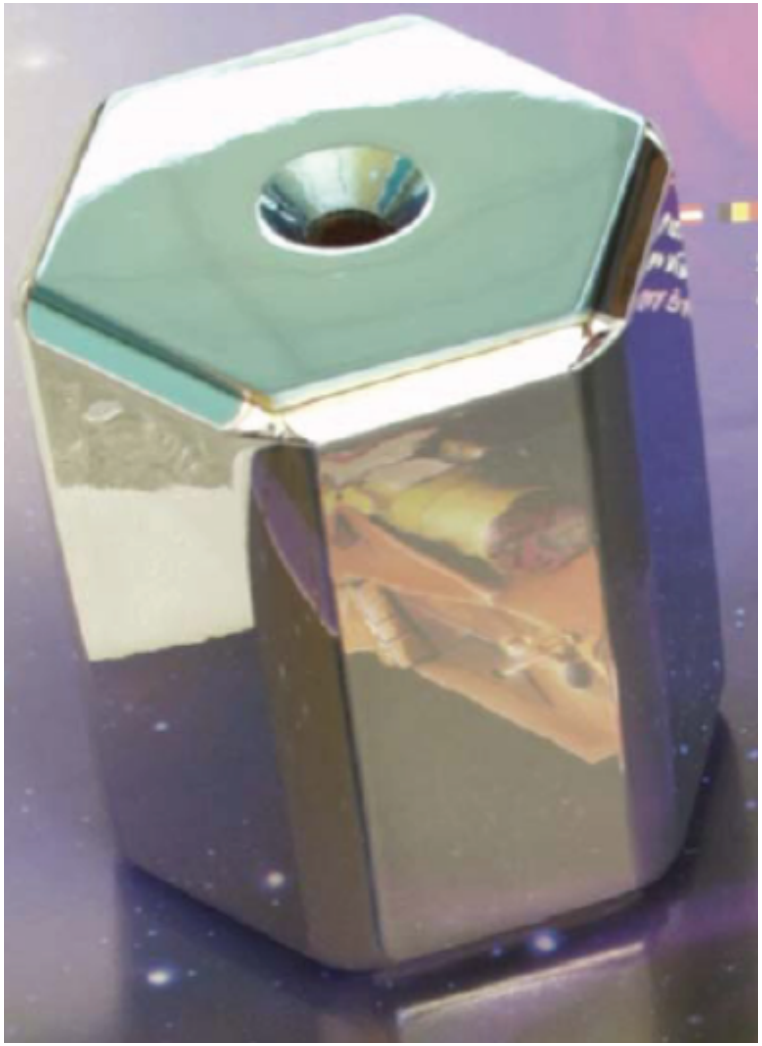
Ge Detectors in Space Telescopes



Detector Cross Section

- Electric potential
- Mechanics
- (RHESSI)

Detector of SPI/INTEGRAL



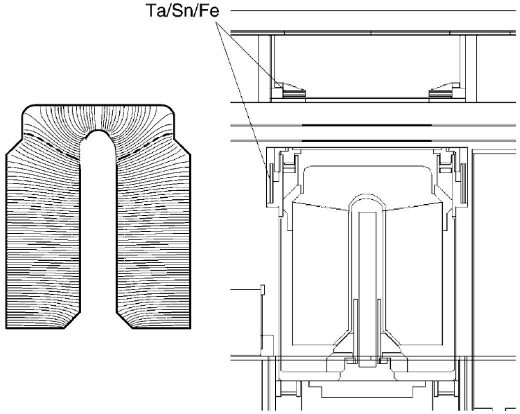
Detector degradation in SPI

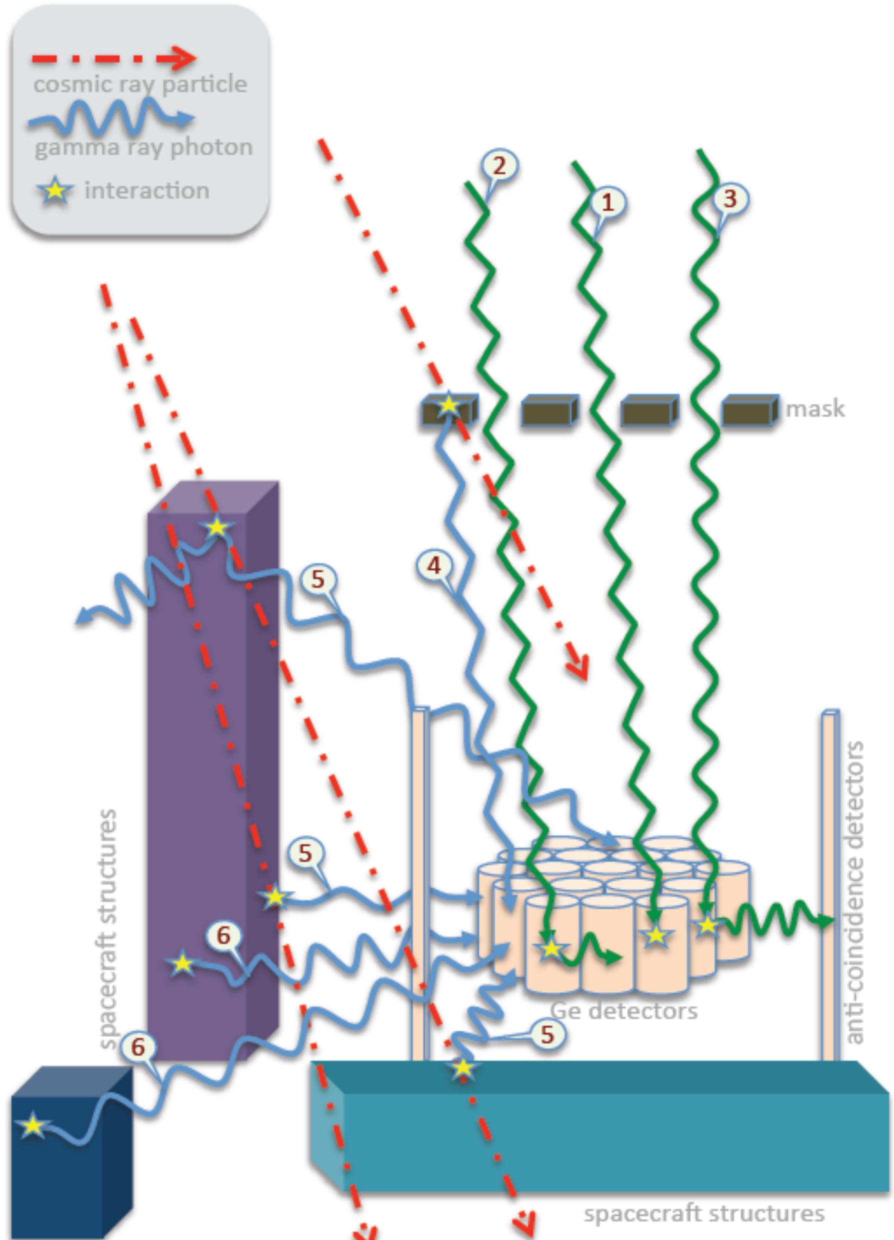
Incident cosmic rays collide with instrument detector nuclei to generate excited daughter nuclei and radioactive by products,

and

to also destroy the Ge detector crystall structure,

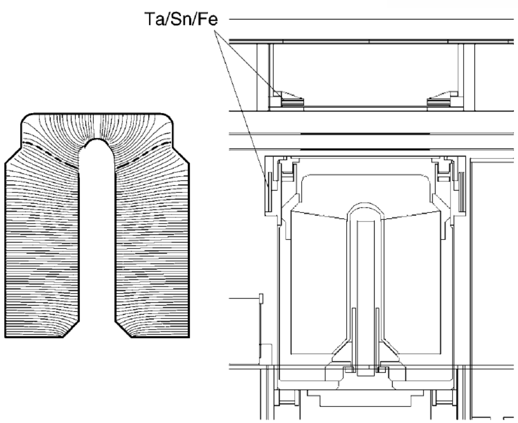
hence **degrade the charge collection efficiency**

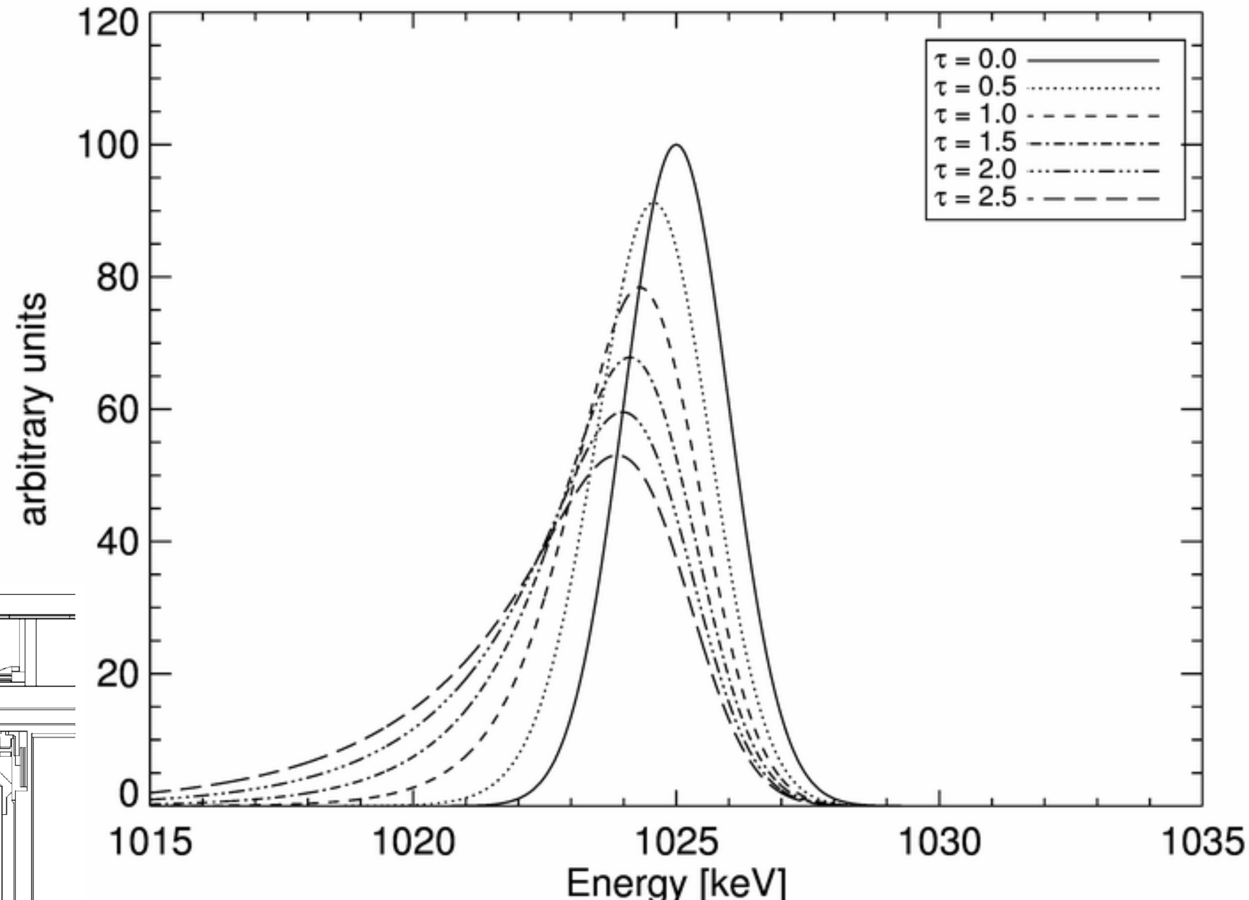




Detector degradation and annealings

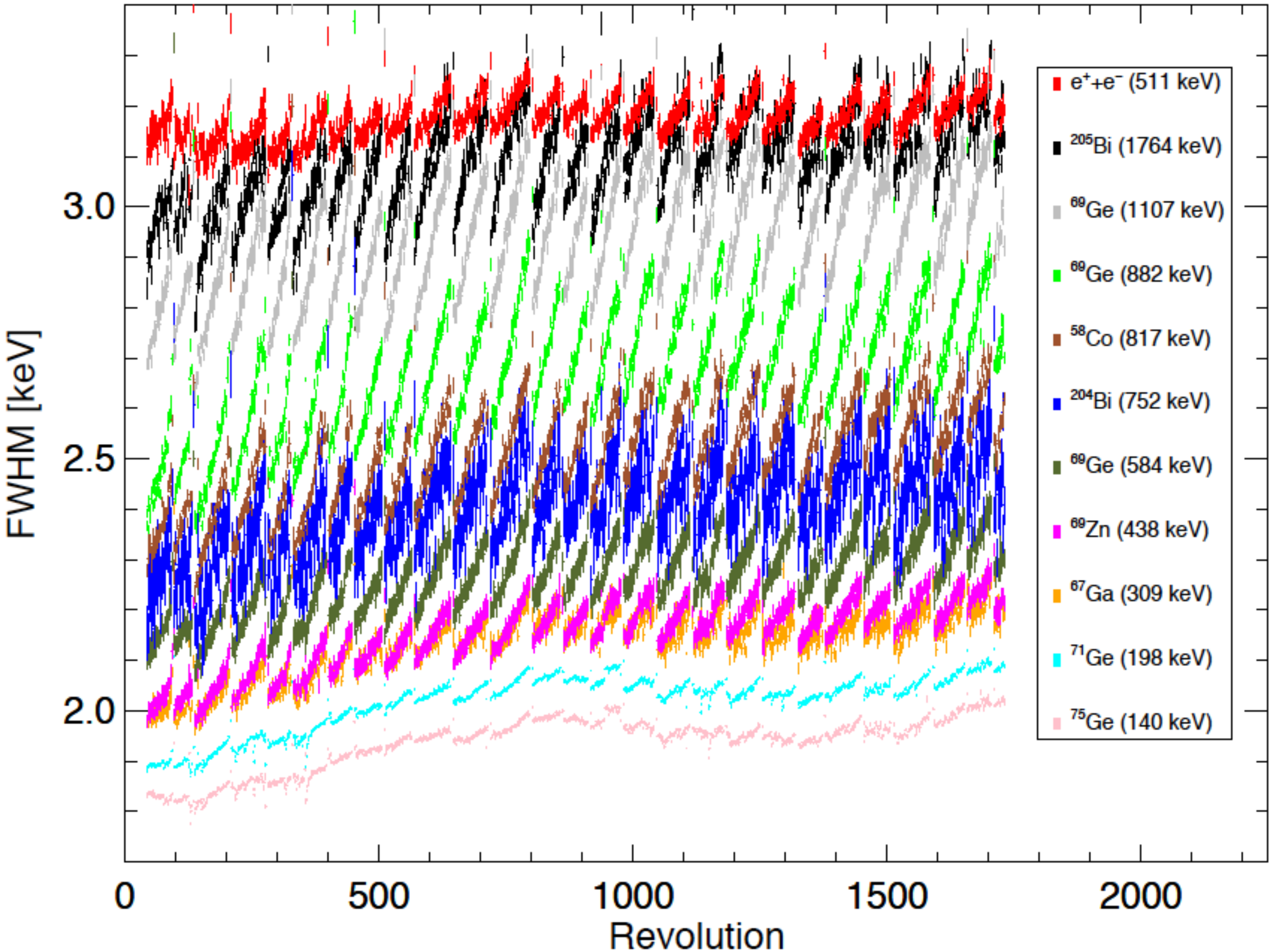
- The instrumental lines are Gaussian in ideal cases
- Degraded charge collection leads to a one-sided bias





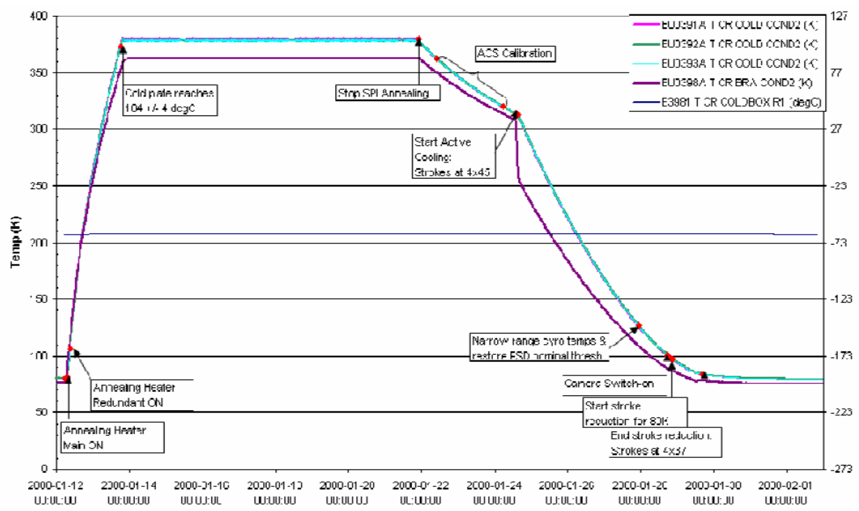
Detector degradation and annealings

-

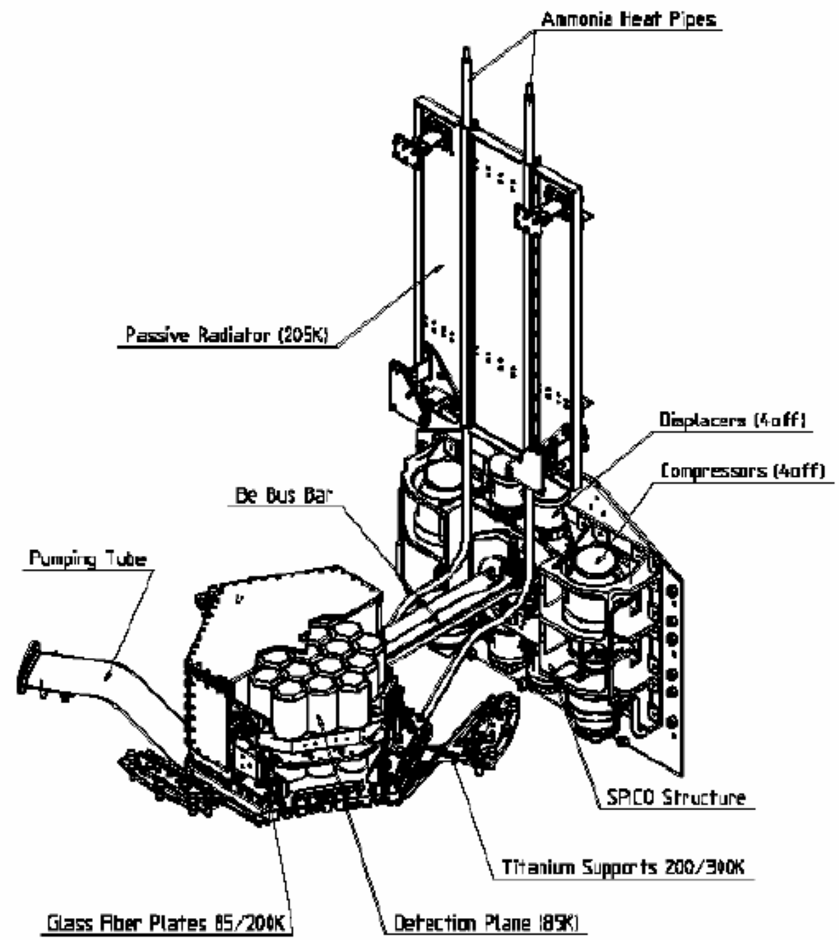


Ge detector annealing in space

- Stirling coolers are turned off, HV off
- Heaters are turned on
- ~100-200 hours at 100° C
- Heaters off, Coolers on
- → 80K operation temperature
- ~2 weeks total duration



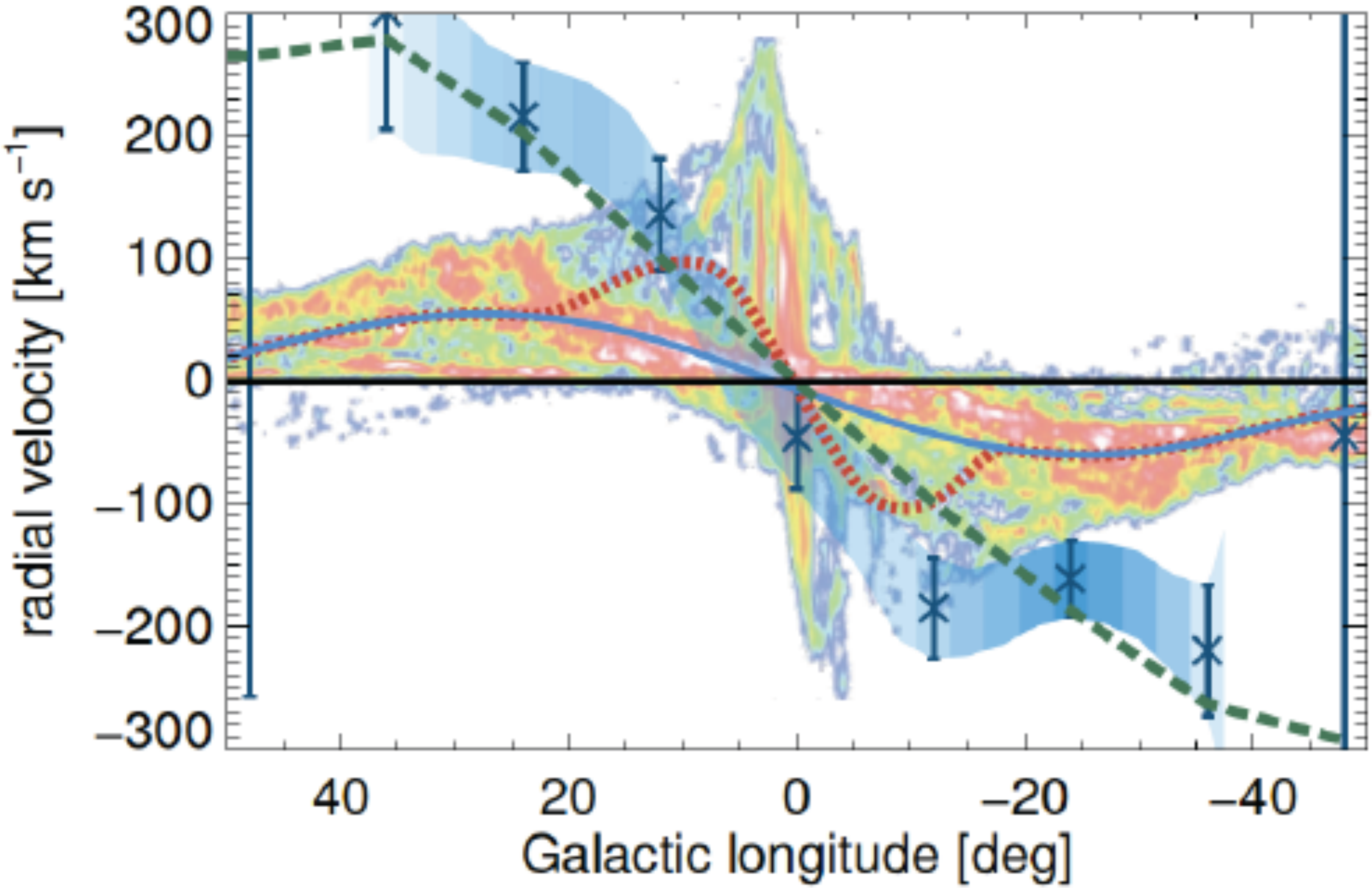
SPI annealing: temperature tracking



SPI Cooling System

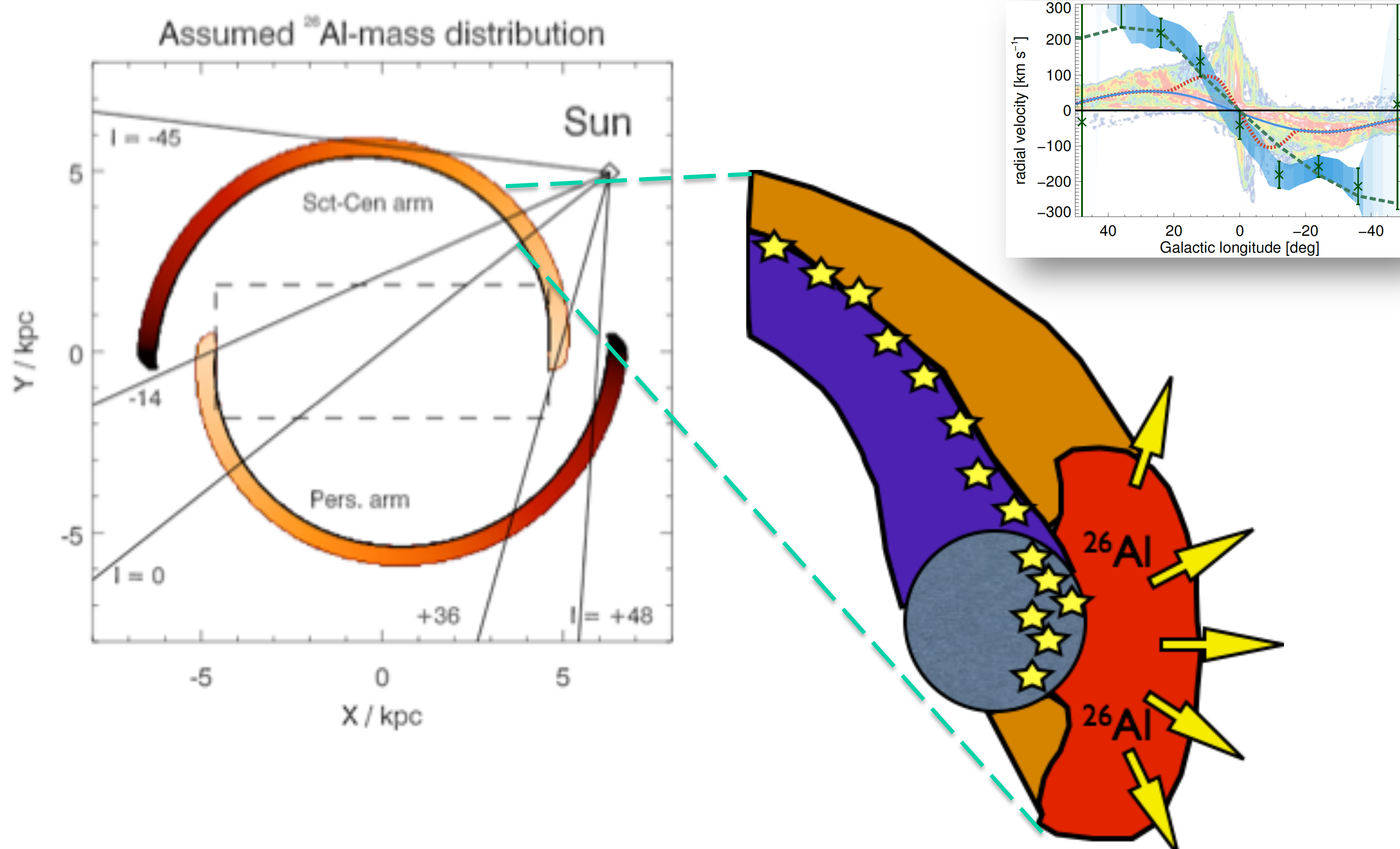
^{26}Al in the Inner Galaxy: Excess Gas Velocities Seen in ^{26}Al

- Comparison of ^{26}Al velocities to others, e.g. CO
  - solid blue: expected if ^{26}Al follows CO densities, and a standard rotation curve is adopted
  - dotted red: same but fraction of ^{26}Al placed in a Galactic Bar
  - green dashed: two-spiral arm distribution of ^{26}Al sources, with enhanced densities towards inner arm ends

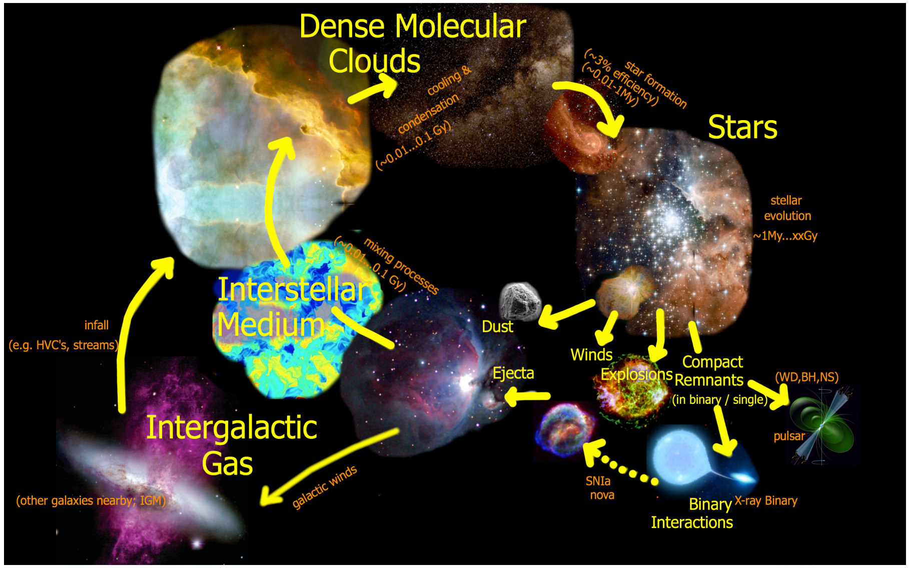


How massive-star ejecta are spread out...

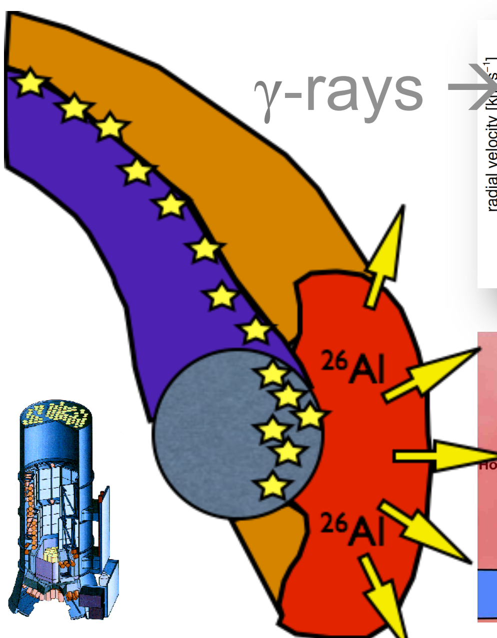
- Superbubbles blown into inter-arm regions

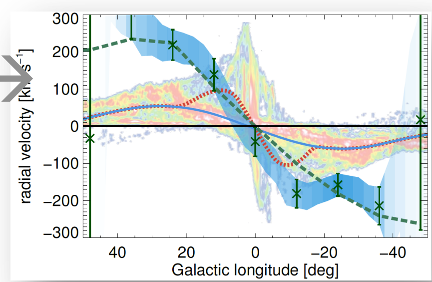


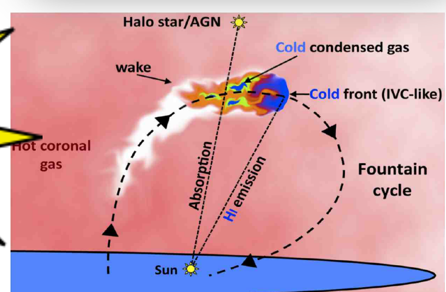
How gas is recycled...

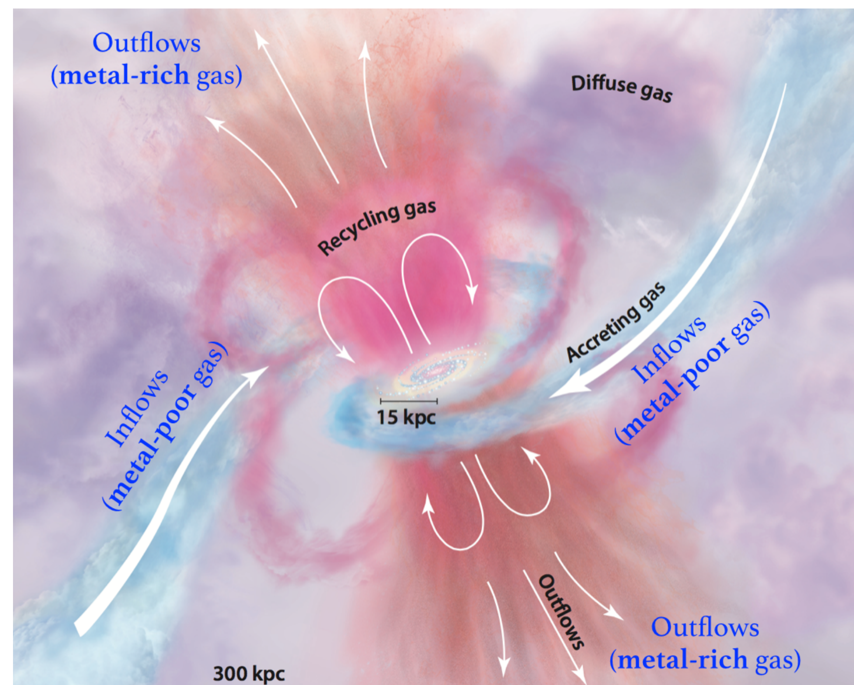


- New nuclei are in hot plasma
- Stars form from cold gas
- Cooling/mixing may depend on source (delay, efficiency)









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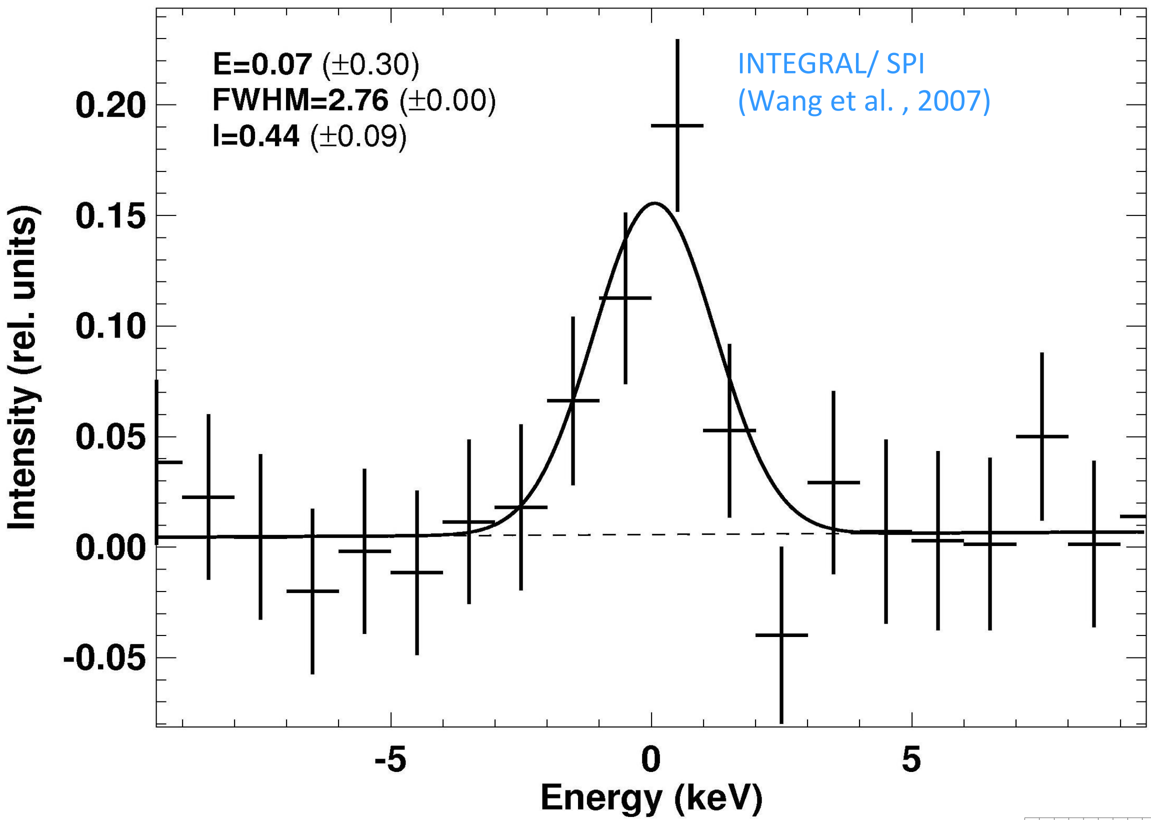
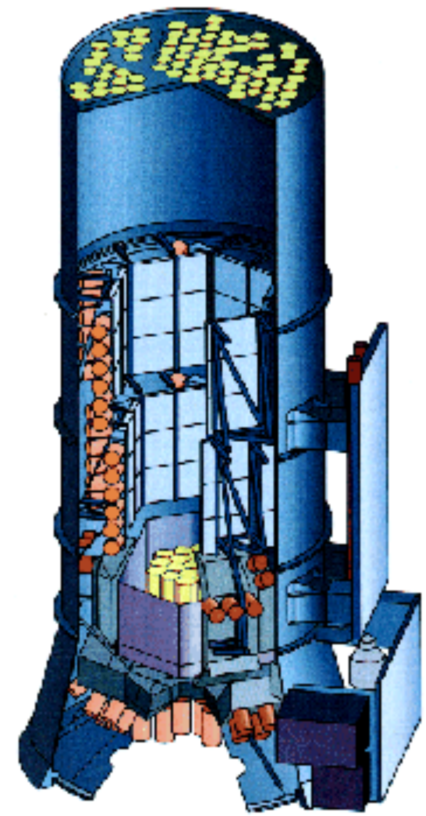
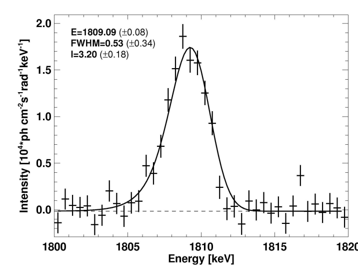
Diffuse ^{60}Fe emission is seen from the Galaxy



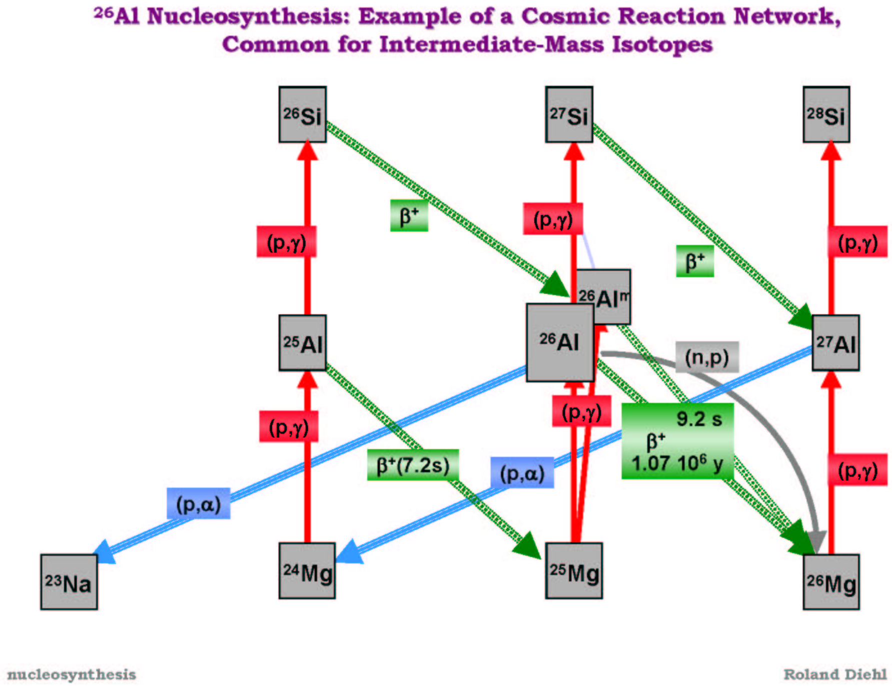




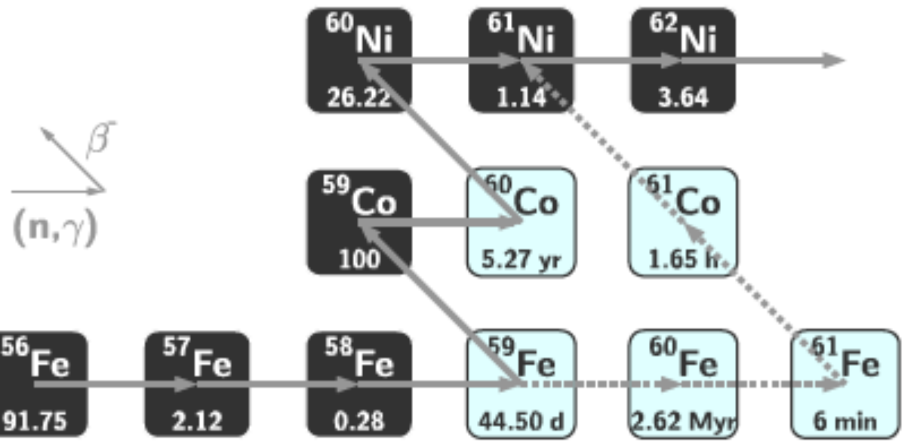
- ☆ Clear but faint gamma-ray signal (5σ)
- ☆ ^{60}Fe/^{26}Al emission ratio ~15%

Nuclear reactions to produce ^{26}Al , ^{60}Fe

- The Na-Al-Mg cycle: p captures (H burning, +...)



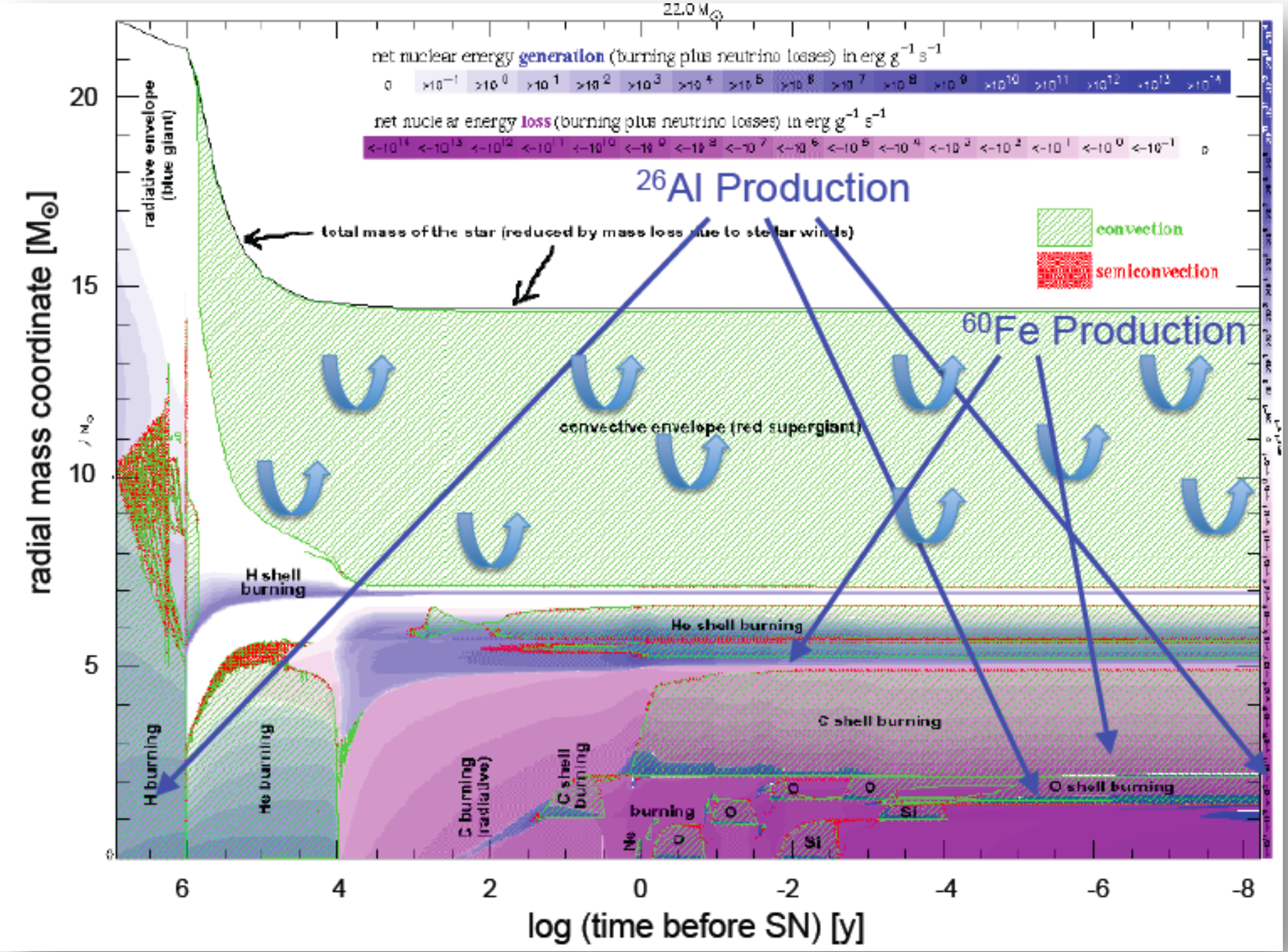
- Neutron capture on Fe in massive-star shells



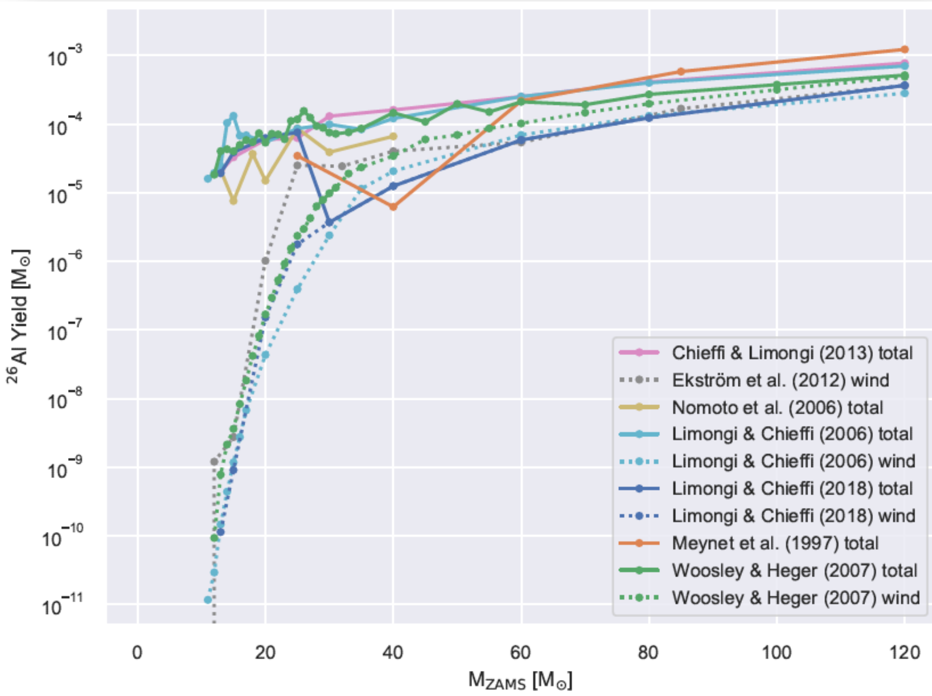
Massive-Star Interiors

(adapted from Heger)

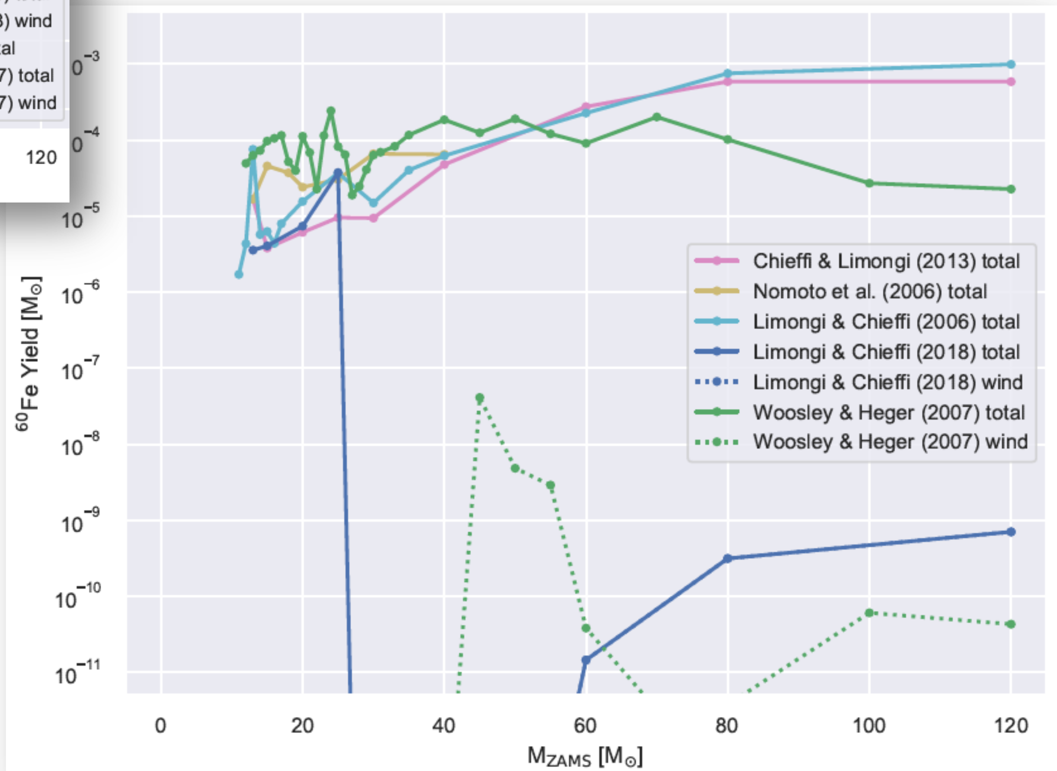
- ☆ *Hydrostatic fusion*
- ☆ *WR wind release*
- ☆ *Late Shell burning*
- ☆ *Explosive fusion*
- ☆ *Explosive release*



Theoretical Yields of ^{26}Al and ^{60}Fe Sources

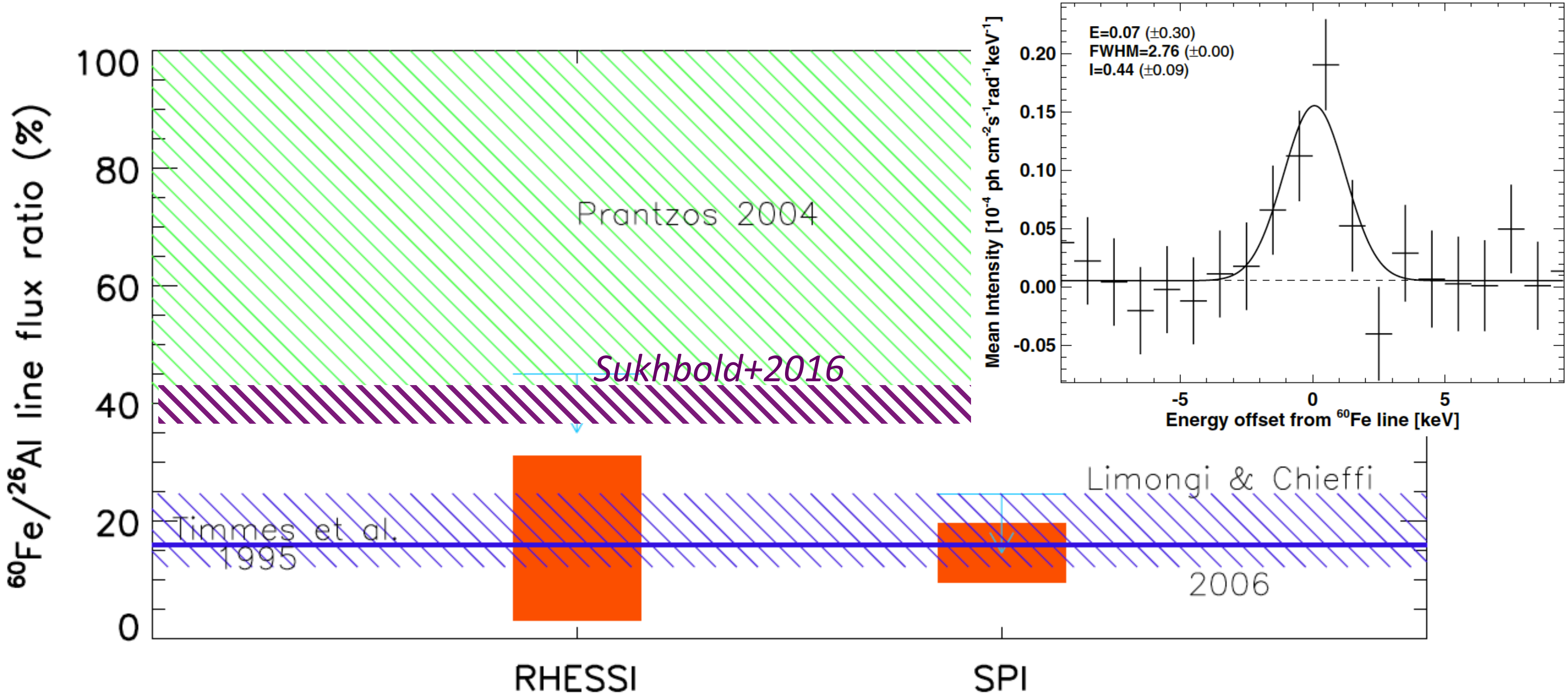


- ☆ Models for massive-star & SN nucleosynthesis
  - Wind ejection
  - Explosive nucleosynthesis addition and SN ejection
    - – *Assembled by M. Pleintinger 2018*



^{60}Fe in the Current Galaxy's ISM

- Observed ^{60}Fe/^{26}Al Intensity Ratio ~15% (±4%)



☞ ^{60}Fe/^{56}Fe isotope ratio in current ISM = $1.5\ 10^{-7}$ (model: $7\ 10^{-4}$ *Sukhbold+2016*)

– using M_{ISM}=4.95 10^9 $M_\odot$ and SAD 7.5 and M_{26Al}=2.25 $M_\odot$ → M_{60Fe}~1.2 $M_\odot$

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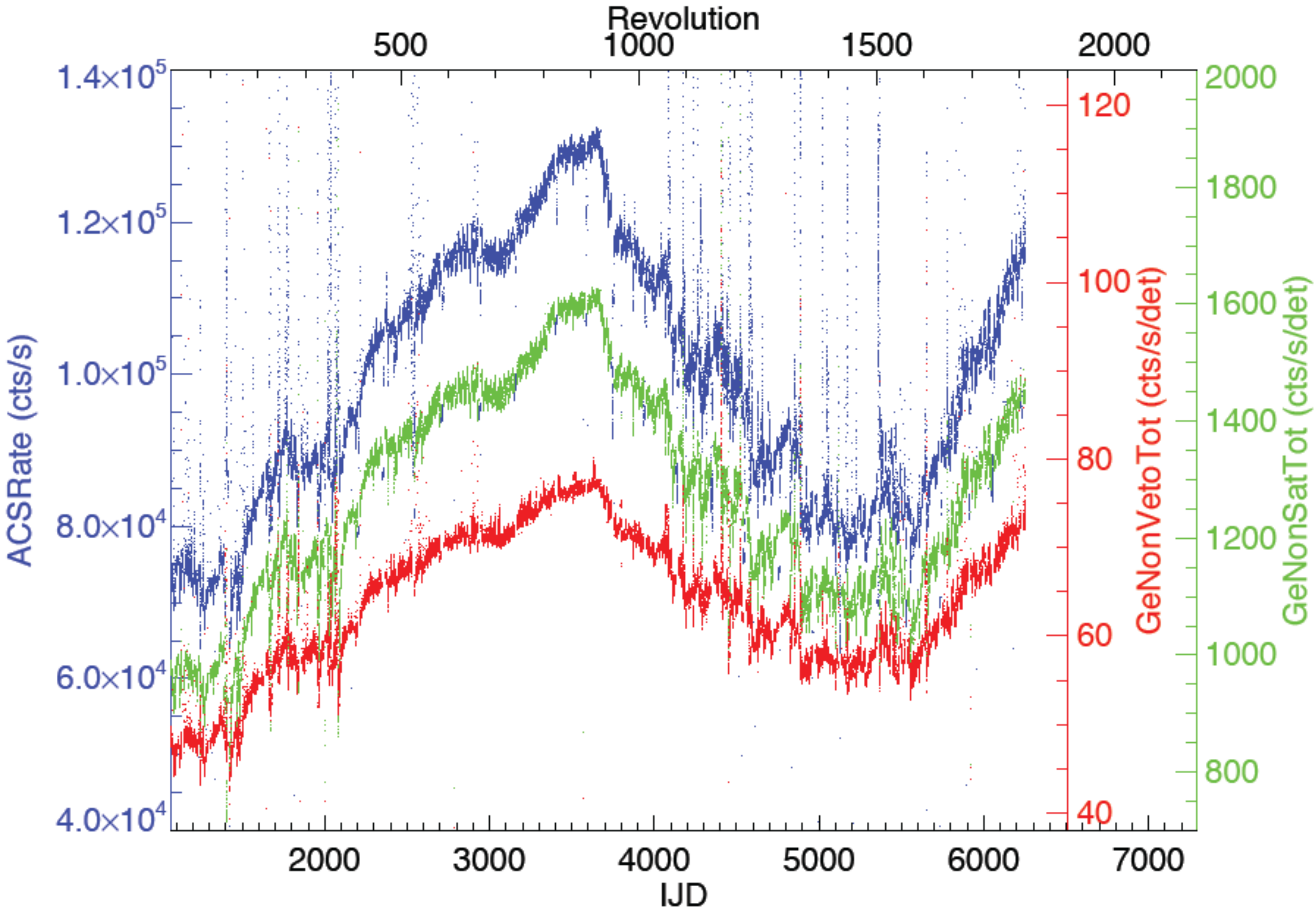
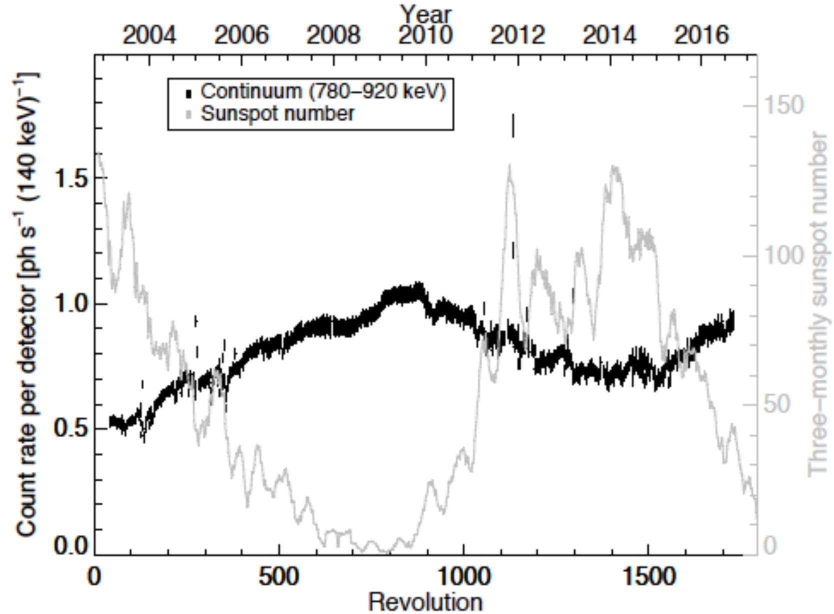
Background history

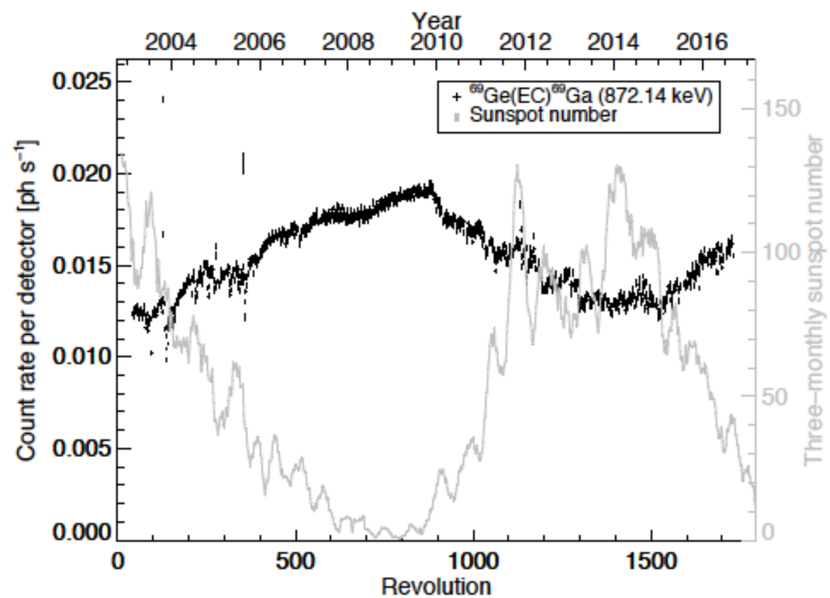
•



Background Variations

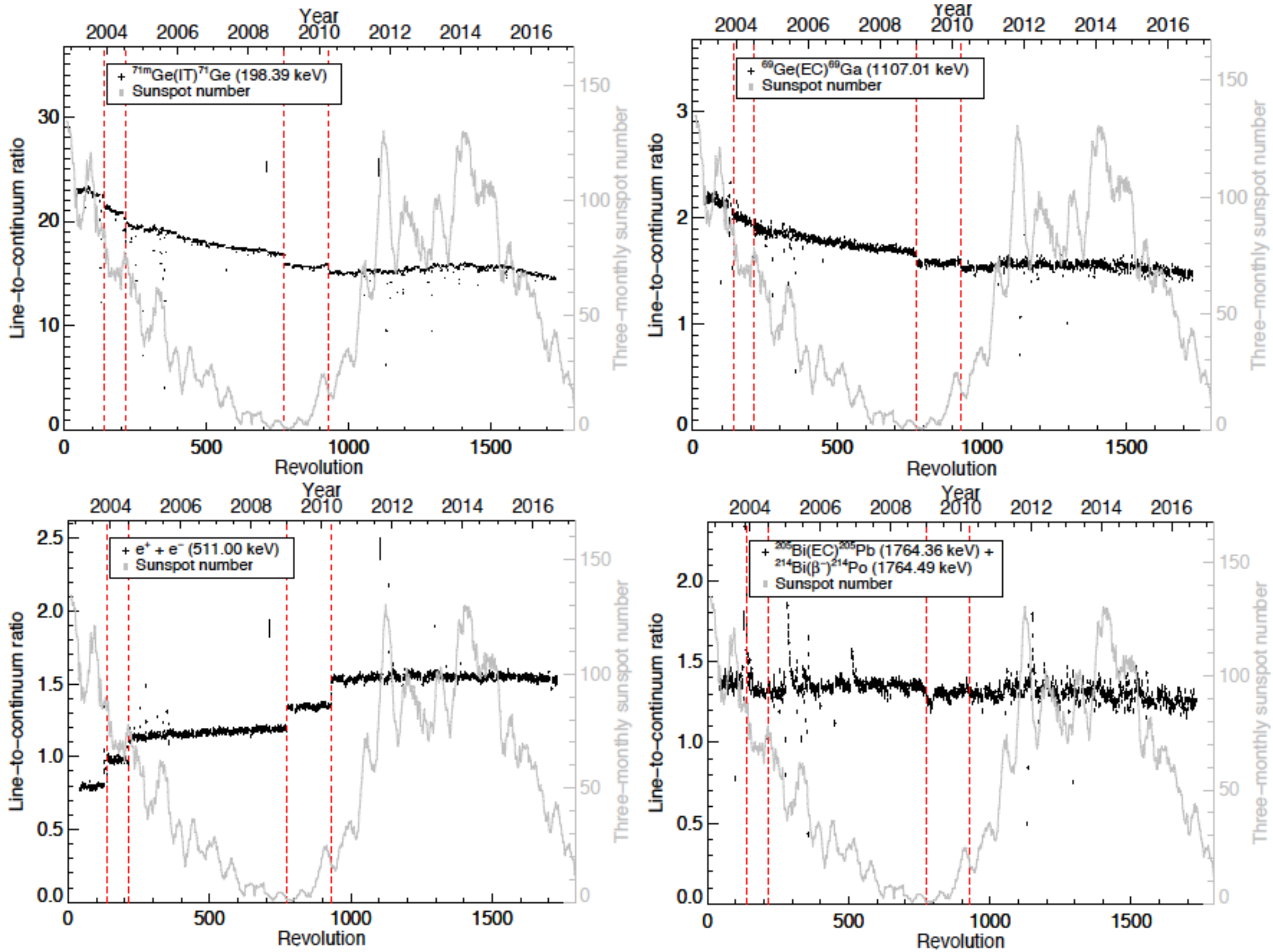
- Specific lines have characteristic variations, in detail different to continuum





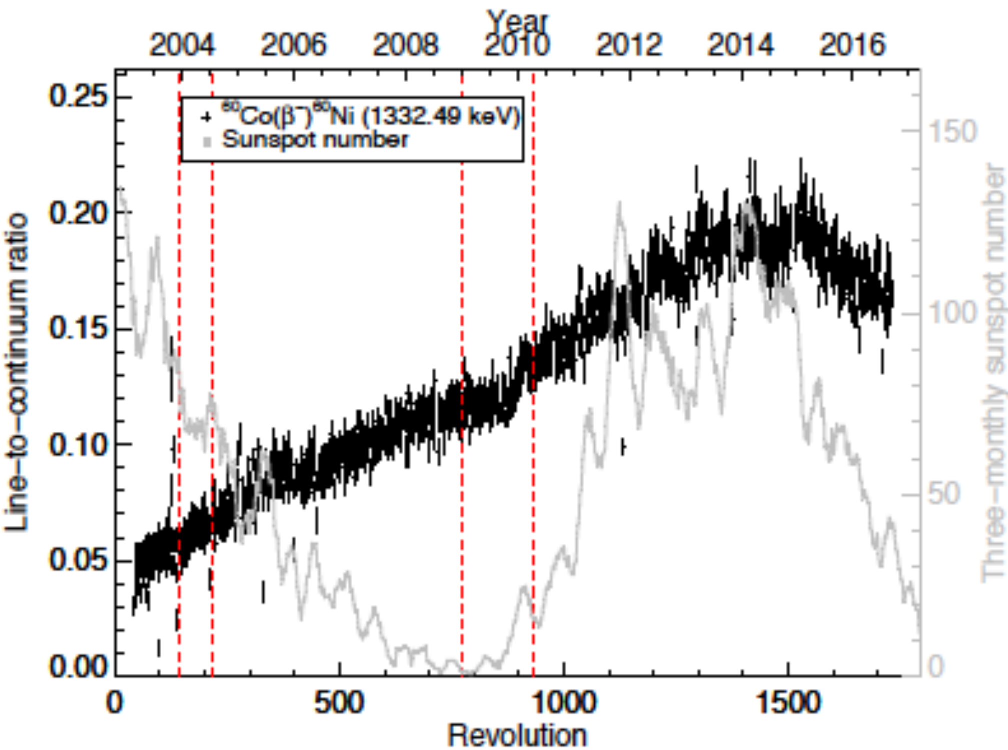
Background Variations

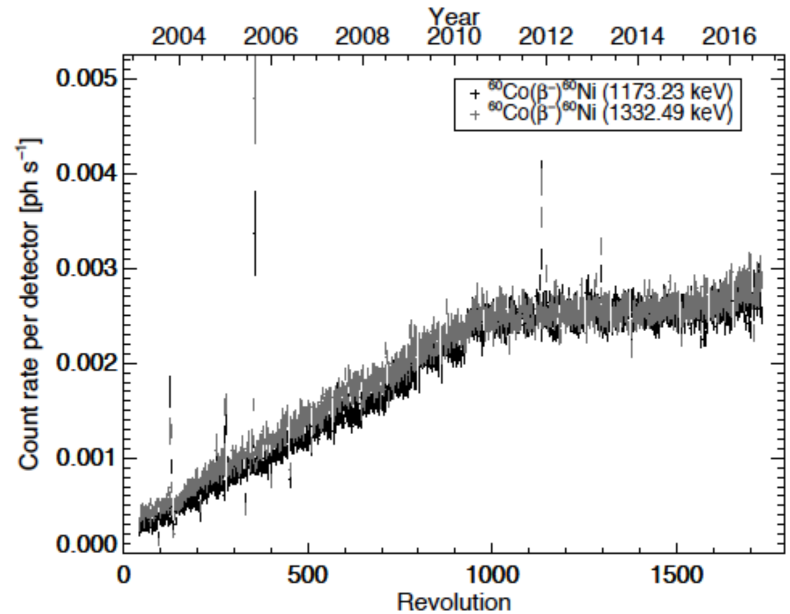
- Specific lines have characteristic variations, different to continuum
  - ☞ Illustrated when normalised:

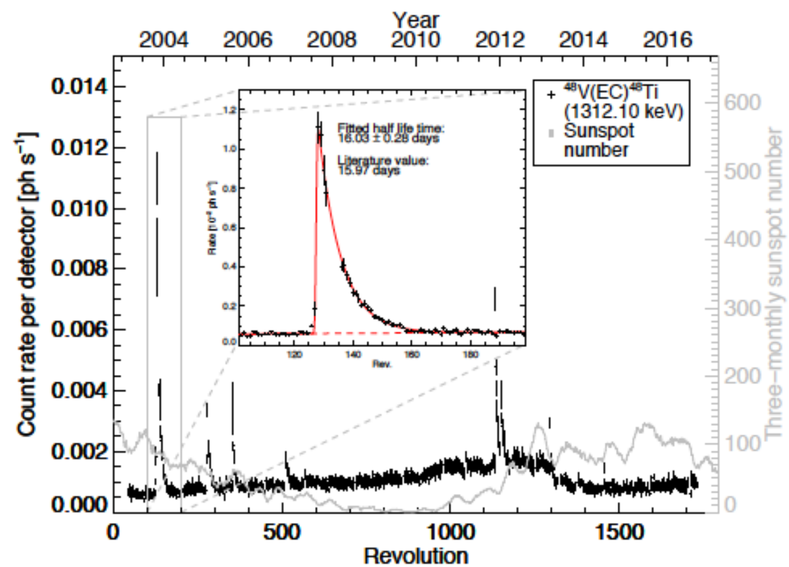


Background Variations

- Activation of materials happens: ^{60}Co, ^{48}V

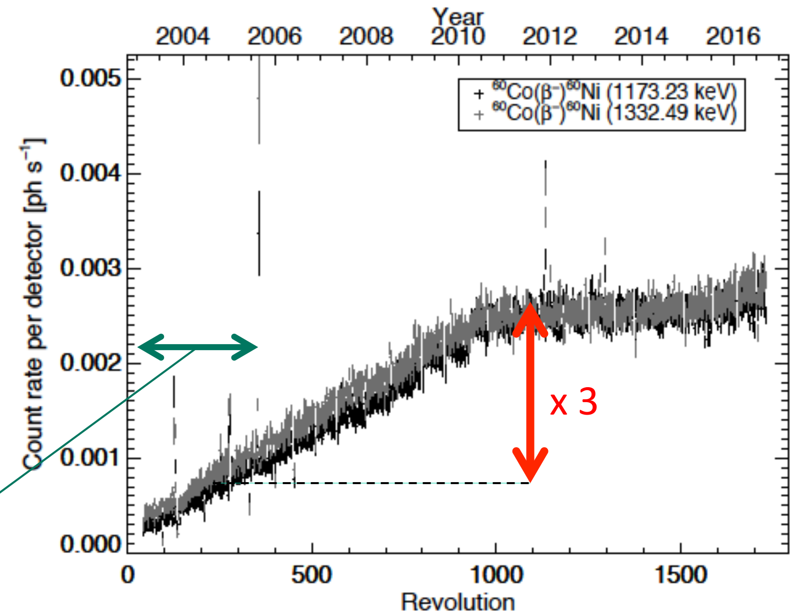




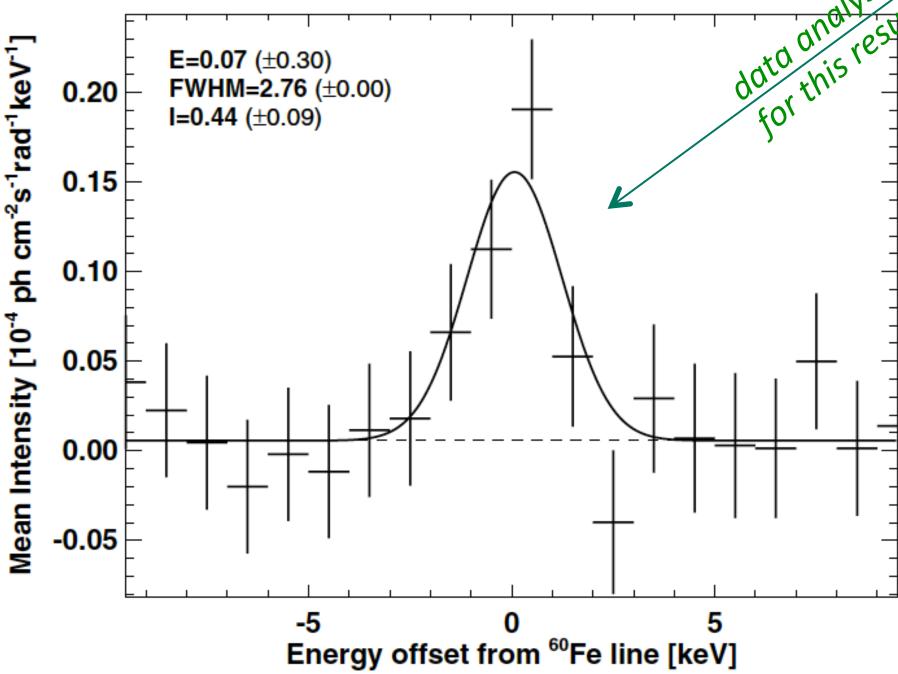


^{60}Fe Analysis SPI

Activation of materials: ^{60}Co

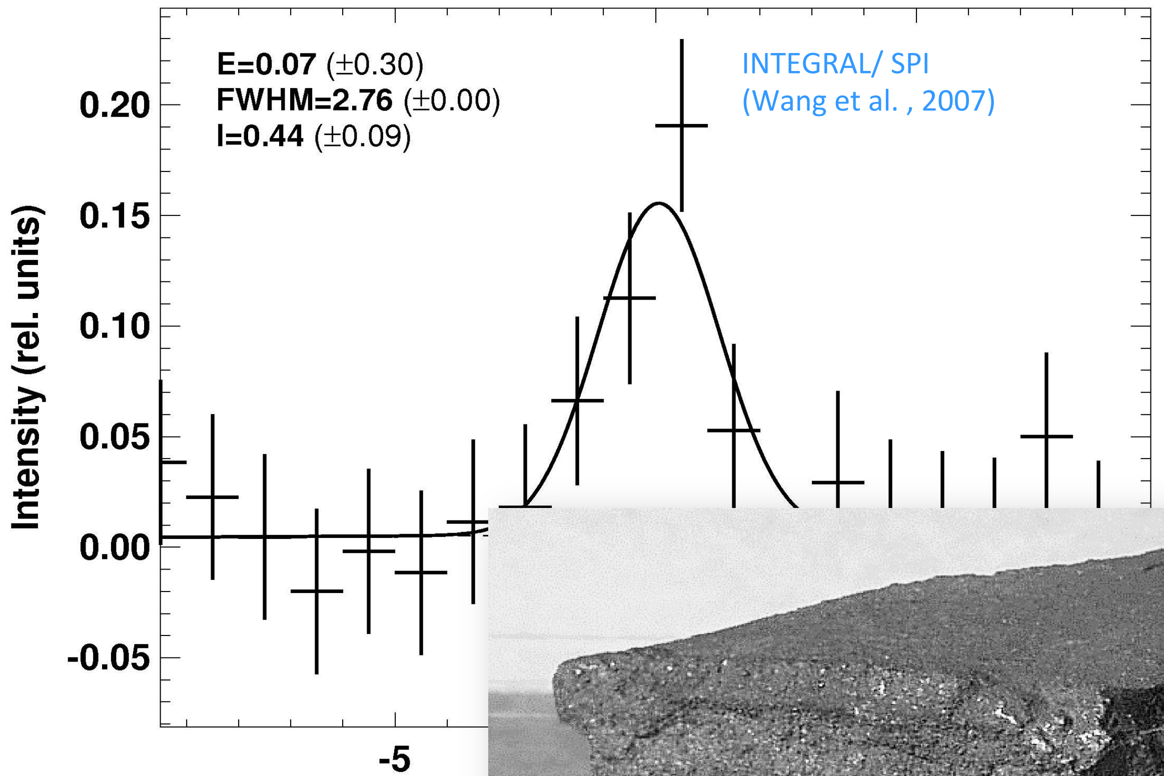


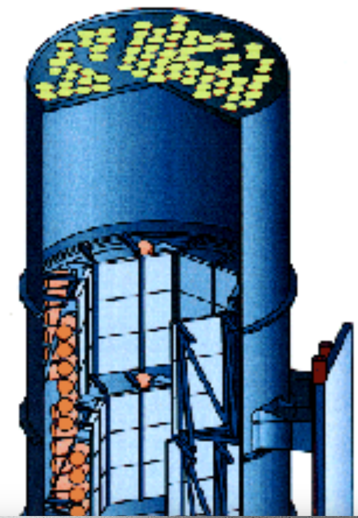
data analysed for this result

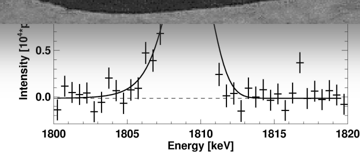


^{60}Fe is a very unfortunate coincidence:
Spallation reactions on Ni, Cu, Zn

Diffuse ^{60}Fe emission is seen from the Galaxy
AND on Earth & Moon





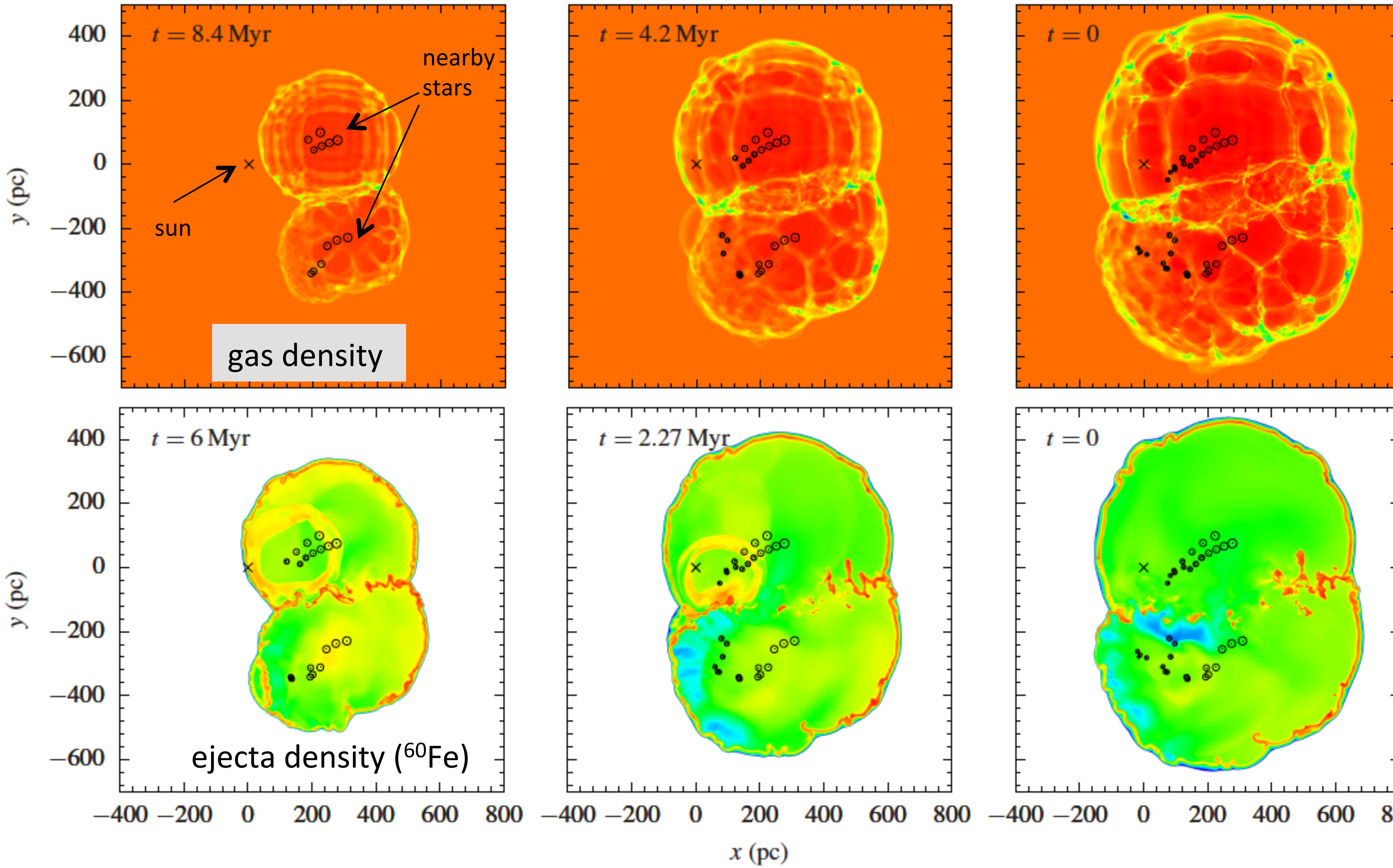


- ☆ Clear but faint gamma-ray signal (3σ)
- ☆ ^{60}Fe/^{26}Al emission ratio ~15%

How ^{60}Fe came onto Earth

- Two local ISM cavities merge (Local Bubble & Loop-1)
- SN explosions within LB → ejecta flows reach the Sun

Schulreich+ 2017



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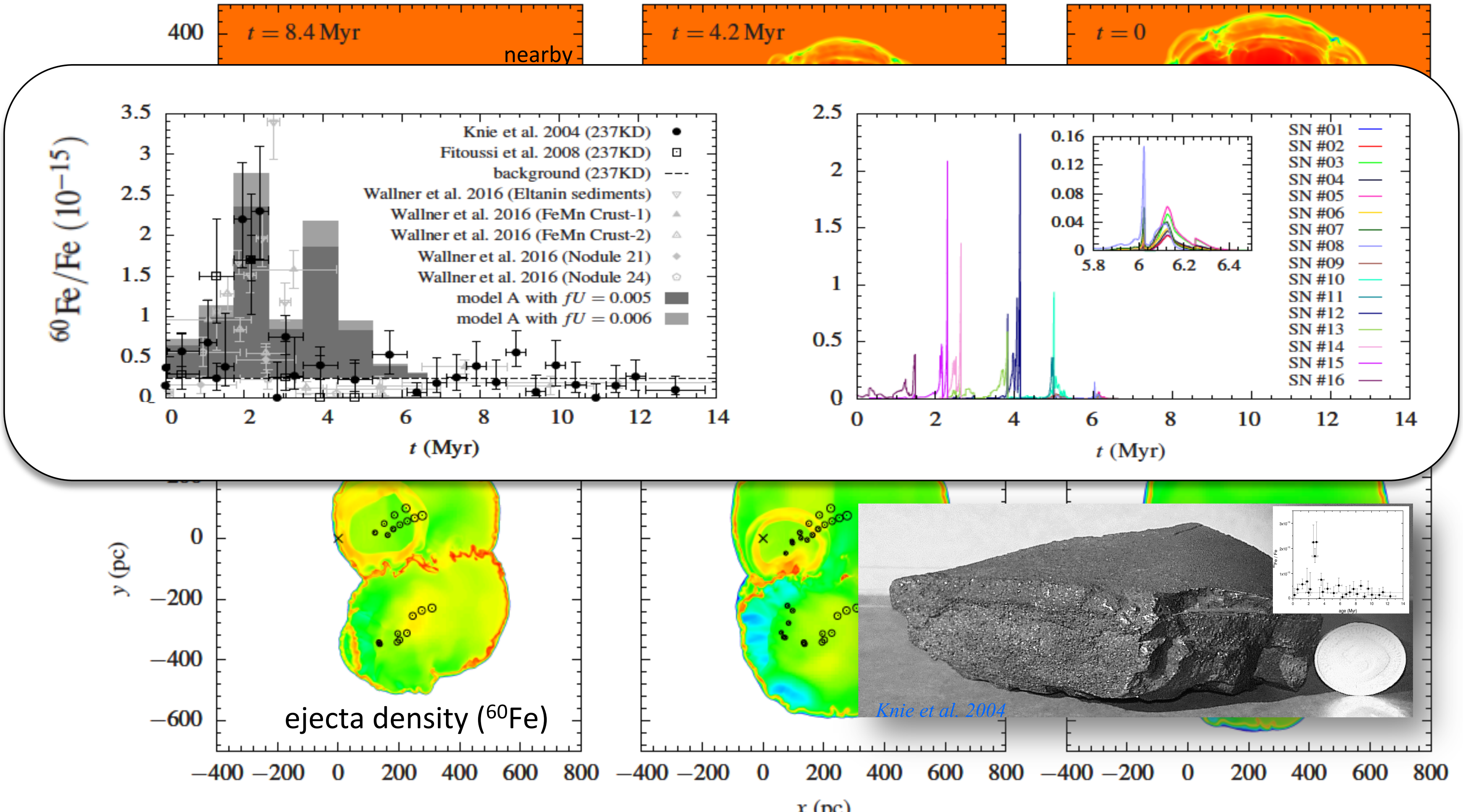


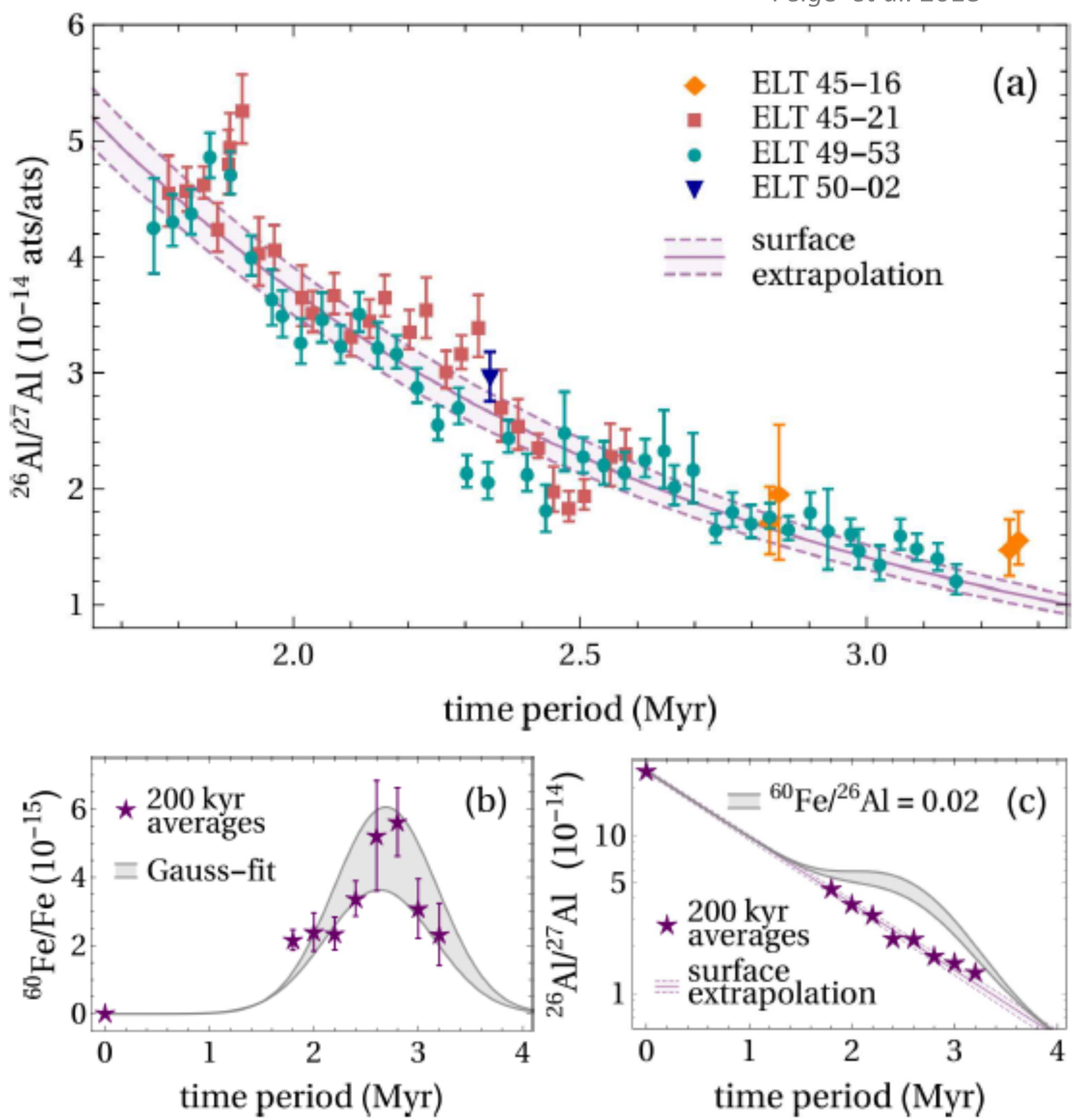
Is nearby ^{60}Fe accompanied by 'typical' ^{26}Al?

- Search for ^{26}Al in deep-sea sediments&crusts
  - ☞ Large 'background' from ^{26}Al that is CR-produced in Earth atmosphere

→ Constraints on ^{26}Al inconsistent with galaxy-wide ratio (0.15)

→ Local: $^{60}Fe/^{26}Al > 0.3$

Feige et al. 2018



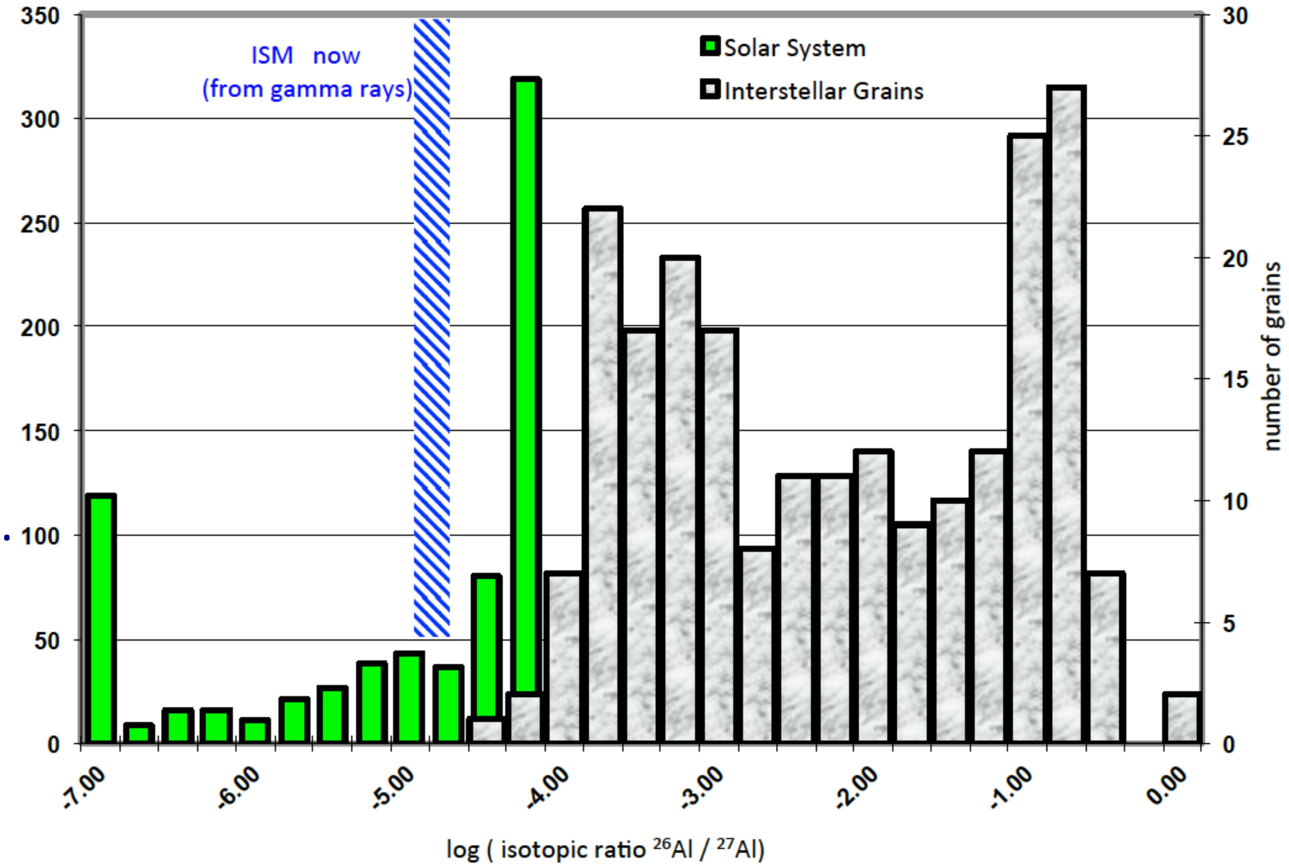
The Al Isotope Ratio

- ^{27}Al is enriched with Galactic Evolution
- ^{26}Al decays, so from current nucleosynthesis
- Early solar system meteorites measure ESS environment
- Pre-solar grains measure nucleosynthesis in dust-producing sources

☆ 'canonical' value for ESS of ~5 10^{-5} *(McPhersson+1995)*

☆ 'supra-canonical' up to 6.5 10^{-5} ?? *(Krot+2012, Makide+ 2013 ..*

☆ Consolidated ESS (5.23±0.13) 10^{-5} *(Jacobsen+2013)*

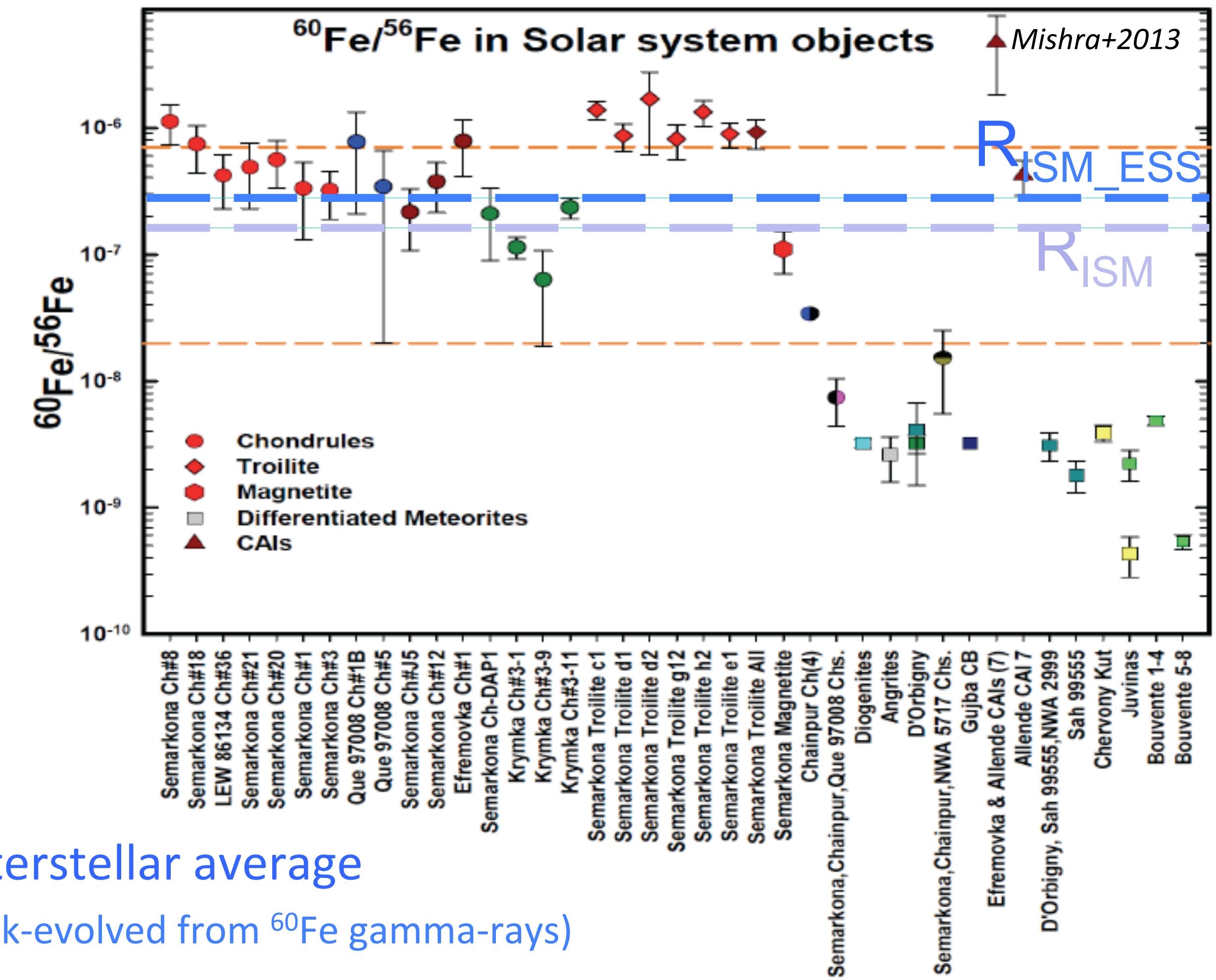


^{60}Fe in the Early Solar System

☆ Measurements from Early-Condensated Bodies:

☞ Initial $^{60}Fe/^{56}Fe$ ratios uncertain between few 10^{-7} and $<10^{-8}$

– *see also Tang & Dauphas 2012; re-inforced by Reto Trappitsch NIC 2018:* 10^{-8}



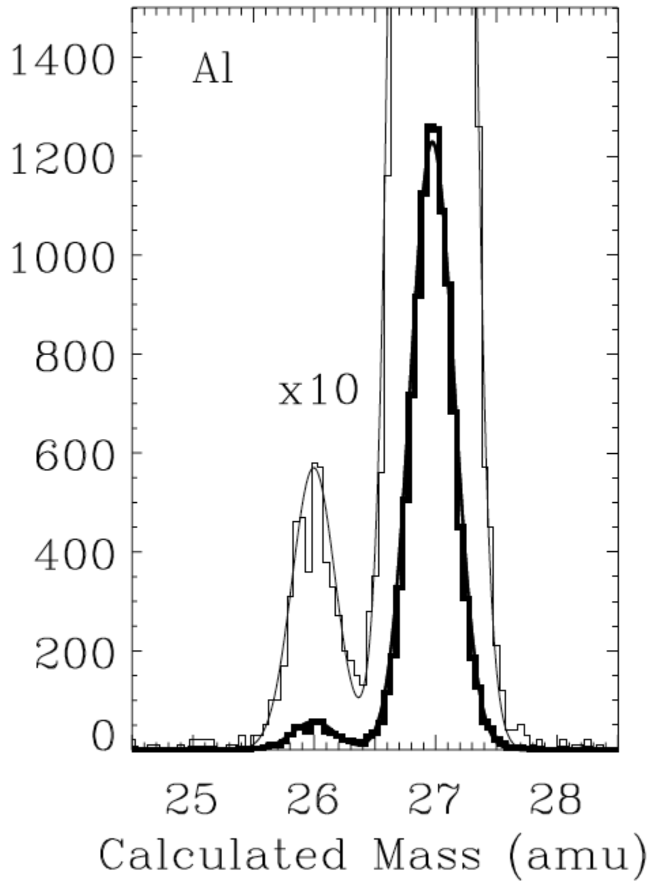
☆ Could be ~ interstellar average

(R_ISM_ESS, back-evolved from ^{60}Fe gamma-rays)

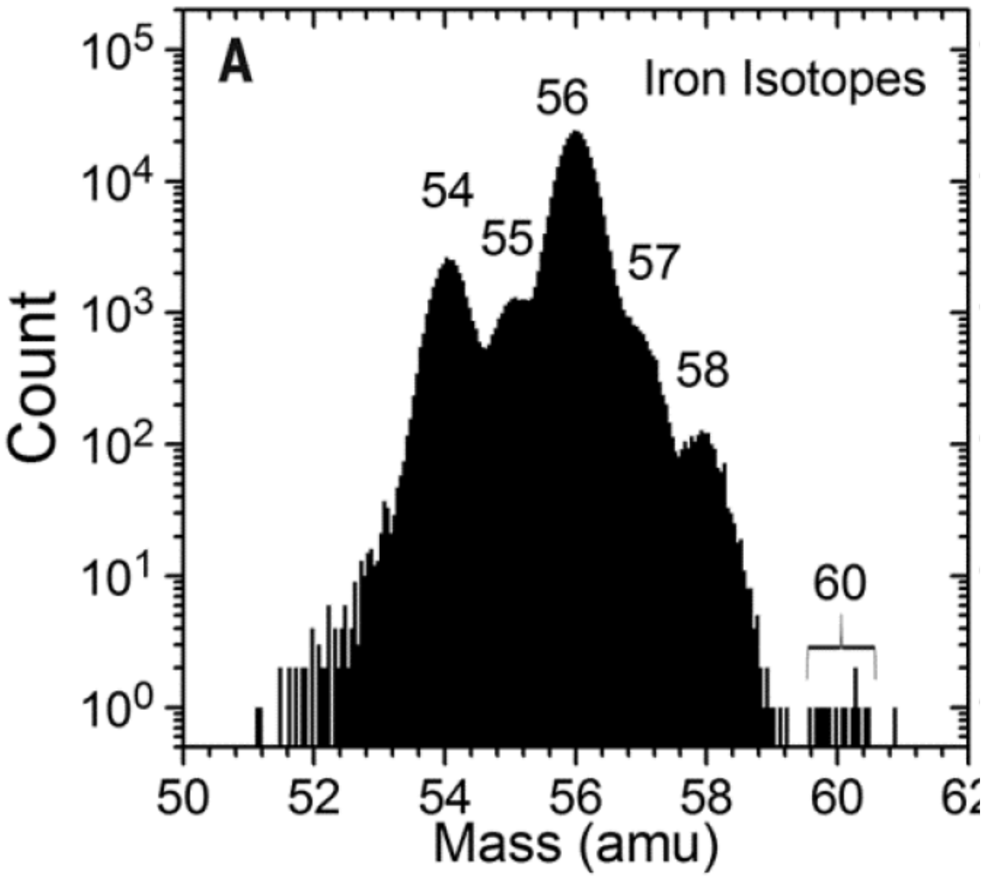
^{26}Al and ^{60}Fe in Cosmic Rays

- Direct measurement in solar system with ACE

Yanasak et al. 2001

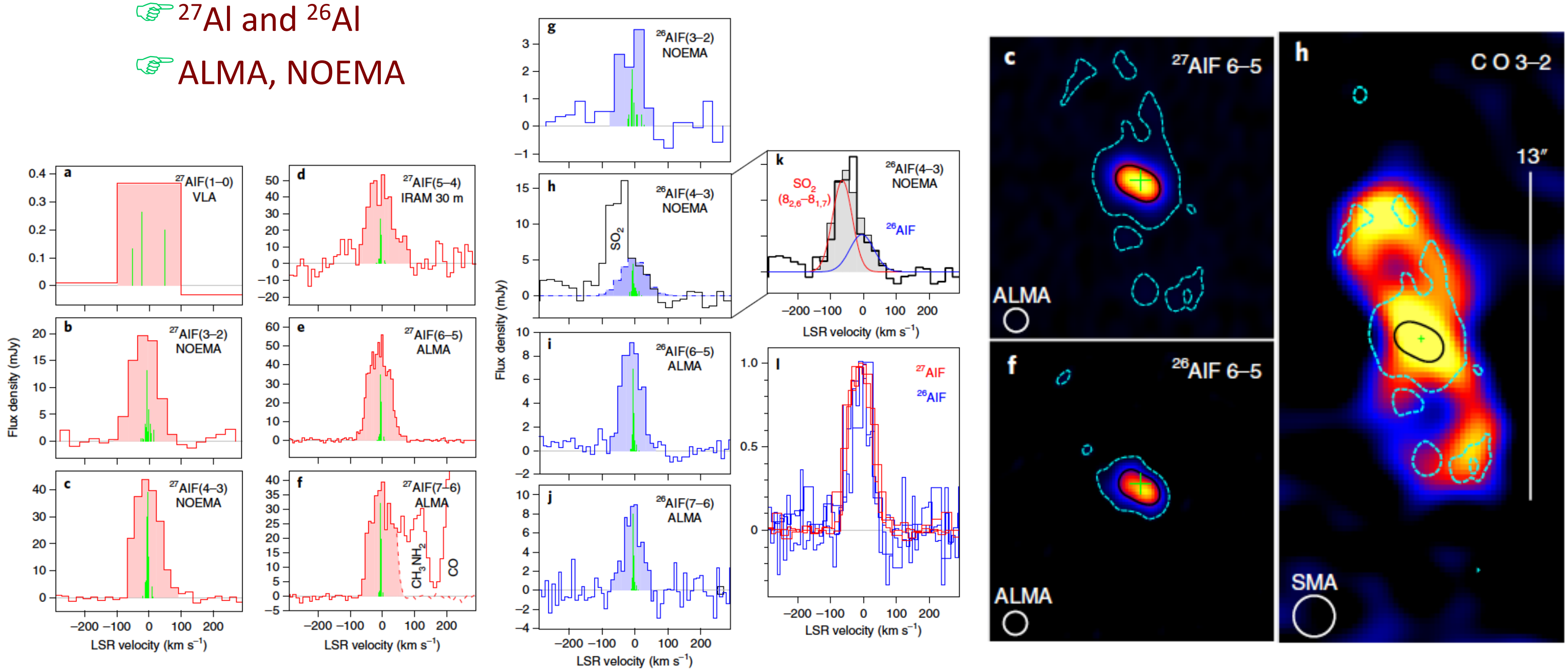


Binns et al. 2016



^{26}Al (in molecular component) in a 'red nova'

- Aluminium monofluoride (AlF) molecule formation happens under special conditions (e.g. after outbursts in binary)
  - ☆ ^{26}AlF line seen from CK Vul (Kamiński et al. 2018)
  - ☆ Favorable line signature of ^{26}AlF → ALMA observations
  - ☆ Dust and molecule formation likely in cooling phase after outburst
  - ☆ Demonstrates existence of ^{26}Al in a stellar source; related to outburst ~1640?
    - ☞ ^{27}Al and ^{26}Al
    - ☞ ALMA, NOEMA



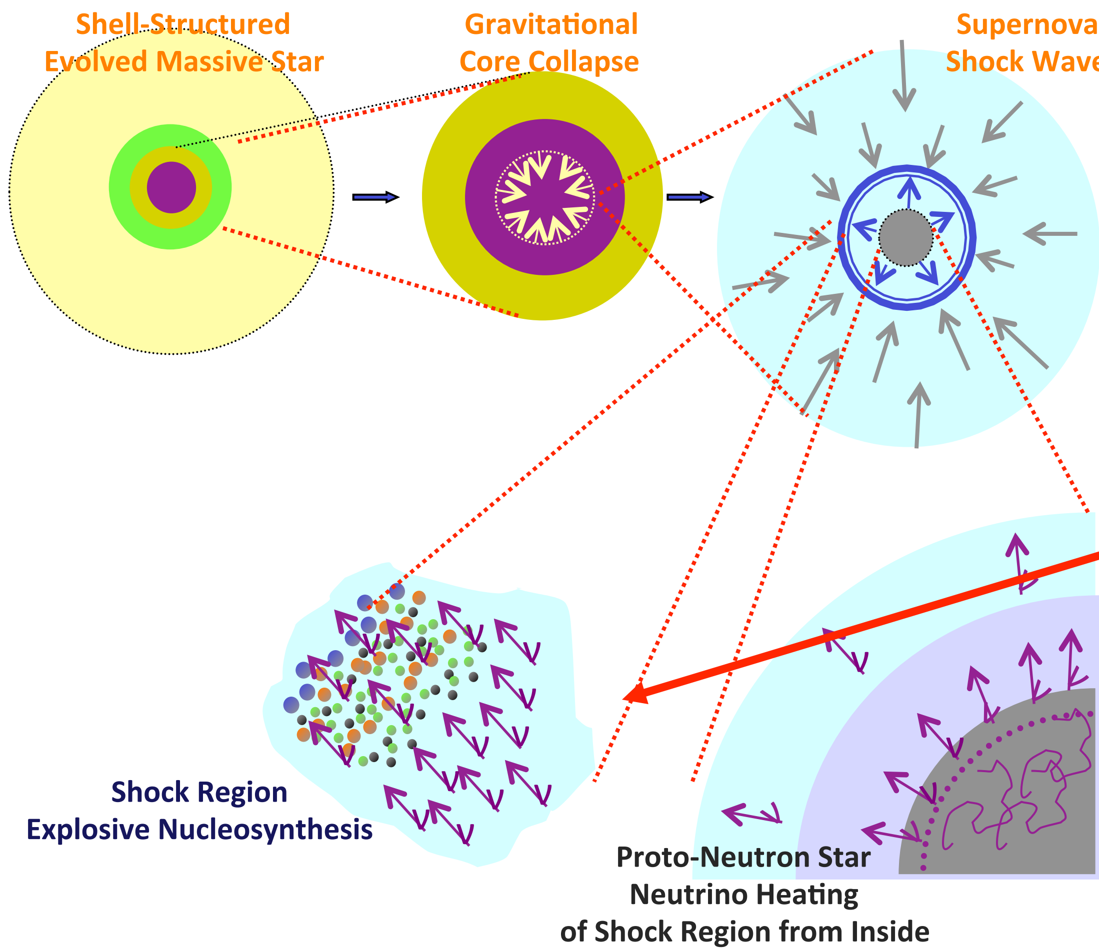
Roland Diehl

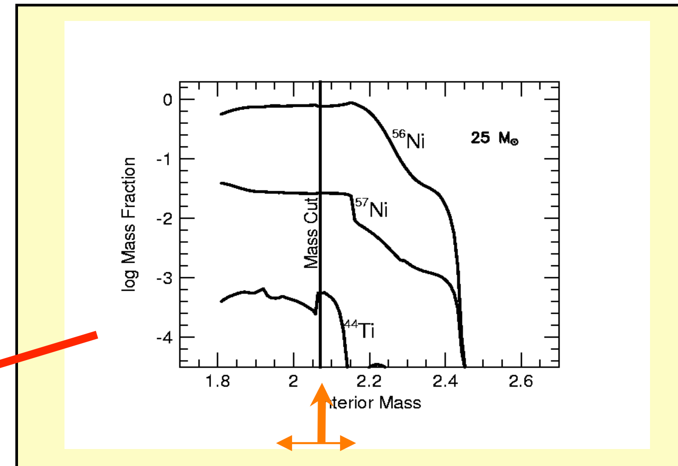
- GETTING THE MOST FOR A POINT SOURCE

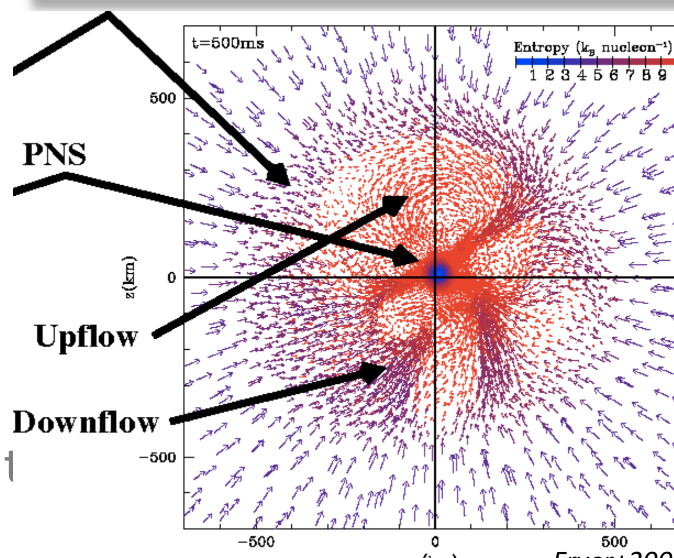
  - ☆ (A Nova)

  - ☆ Supernovae
    - ☞ SN2014J
    - ☞ Cas A

Nucleosynthesis in CC-Supernova Models and ^{44}Ti







Fryer+2008

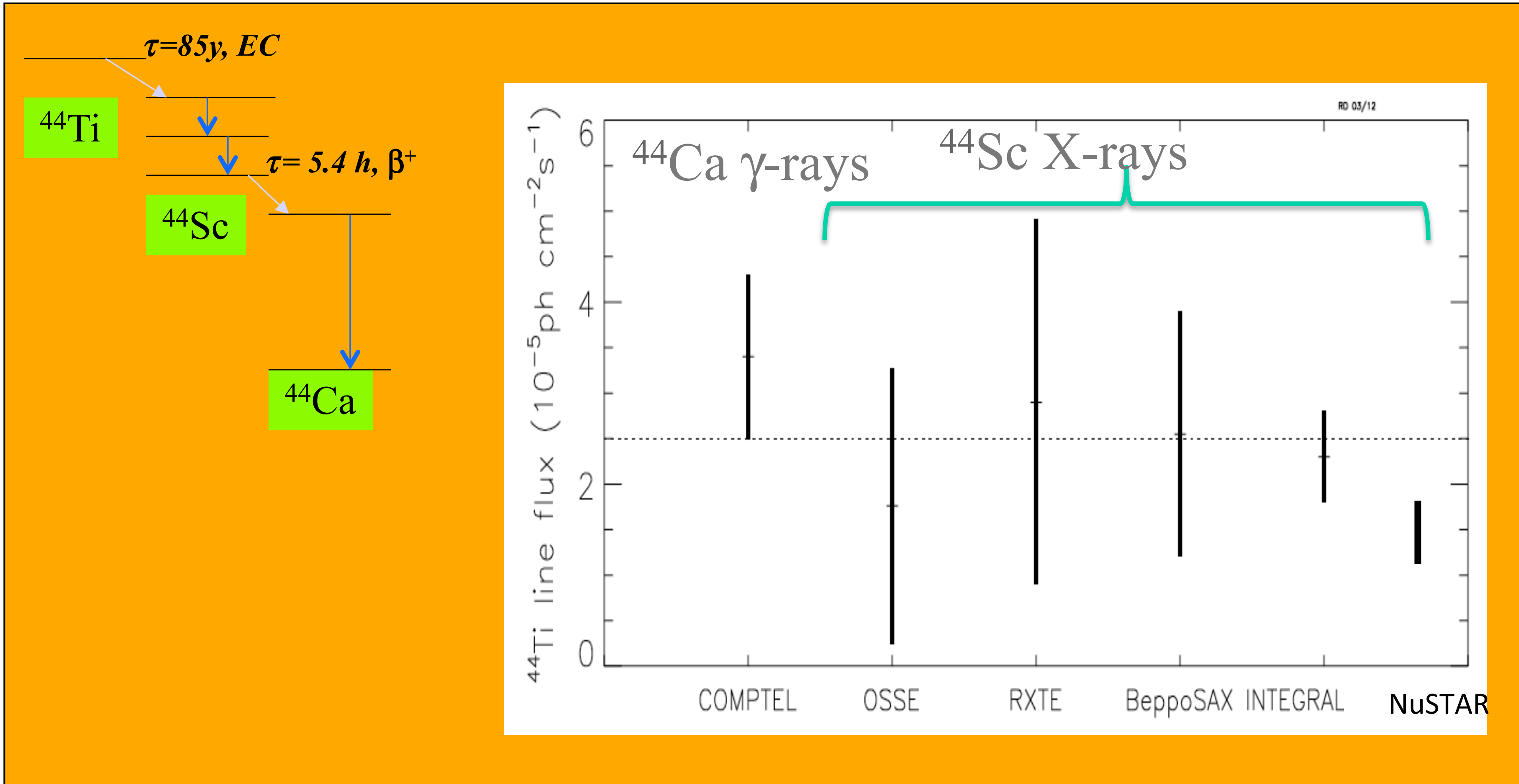
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out

=> Unique Probe (+Ni Isotopes)

^{44}Ti γ-rays from Cas A

t=85y (Ahmad et al. 2006)

89 y	$^{44}Ti \rightarrow ^{44}Sc^* \rightarrow ^{44}Ca^* + e^+$	78, 68; 1157



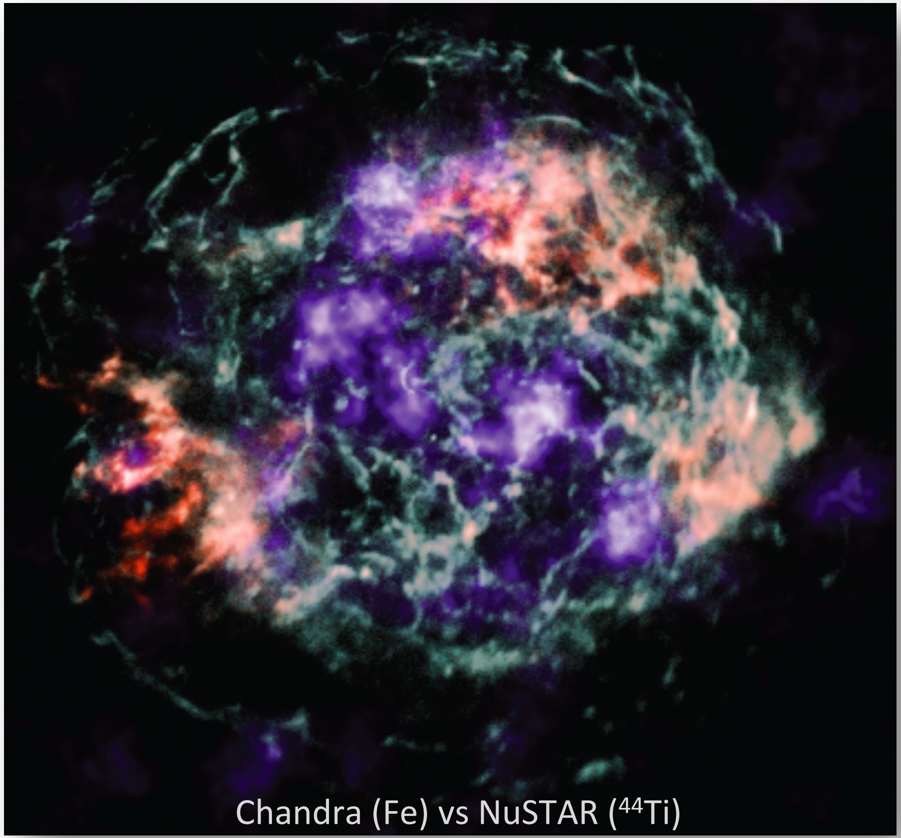
↳ ^{44}Ti Ejected Mass ~1.23 ±0.25 10^{-4} $M_\odot$

NuSTAR measurement of ^{44}Ti in Cas A

Imaging in hard X-rays (3-79 keV) → ^{44}Ti lines at 68,78 keV

☞ Cas A: first mapping of radioactivity in a SNR

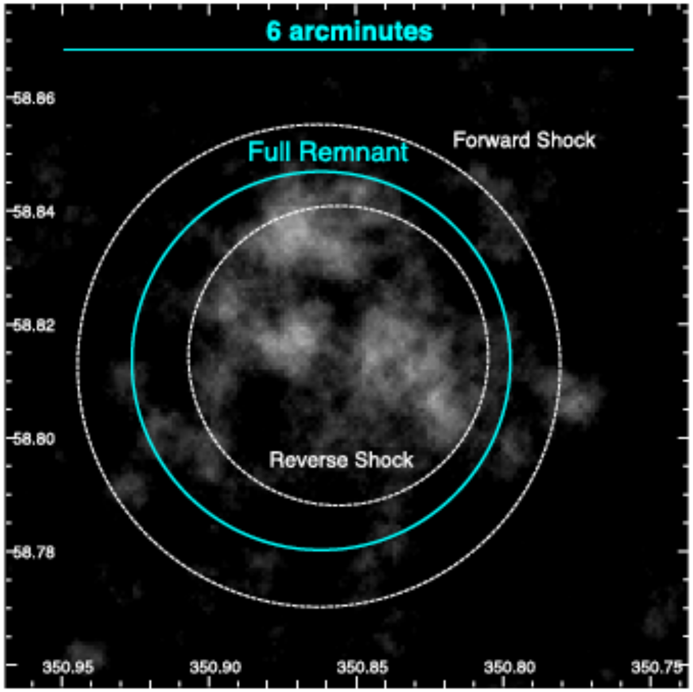
- Both ^{44}Ti lines detected clearly
- line redshift 0.5 keV
  → 2000 km/s redshift asymmetry
- ^{44}Ti flux consistent with earlier measurements
- Doppler broadening: (5350 ±1610) km s^{-1}
- Image differs from Fe!!

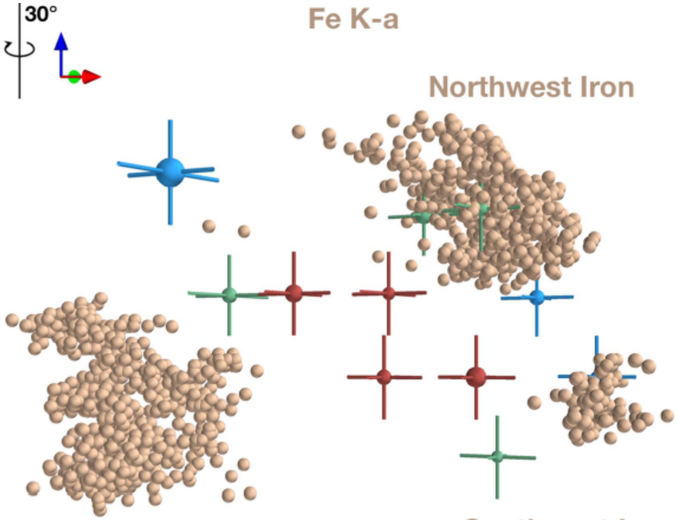


Grefenstette et al. 2014

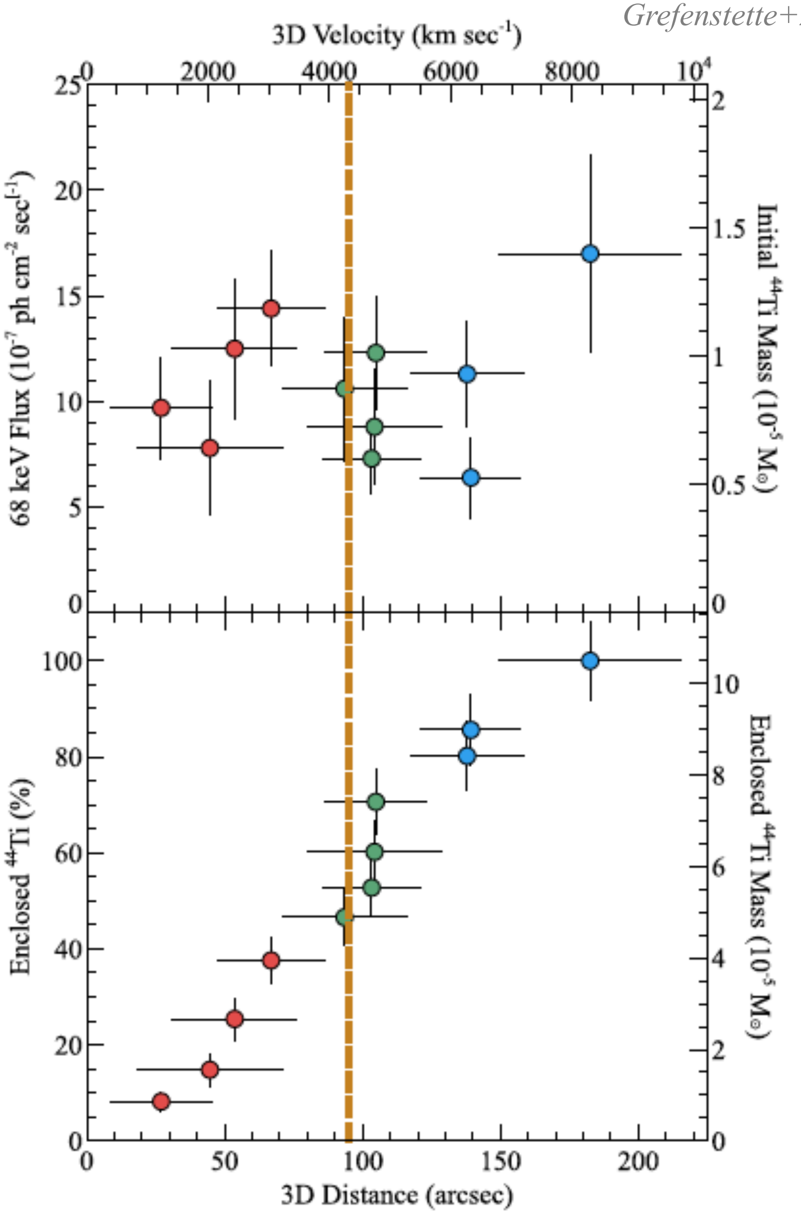
Where are the ^{44}Ti Ejecta in the SNR?

-



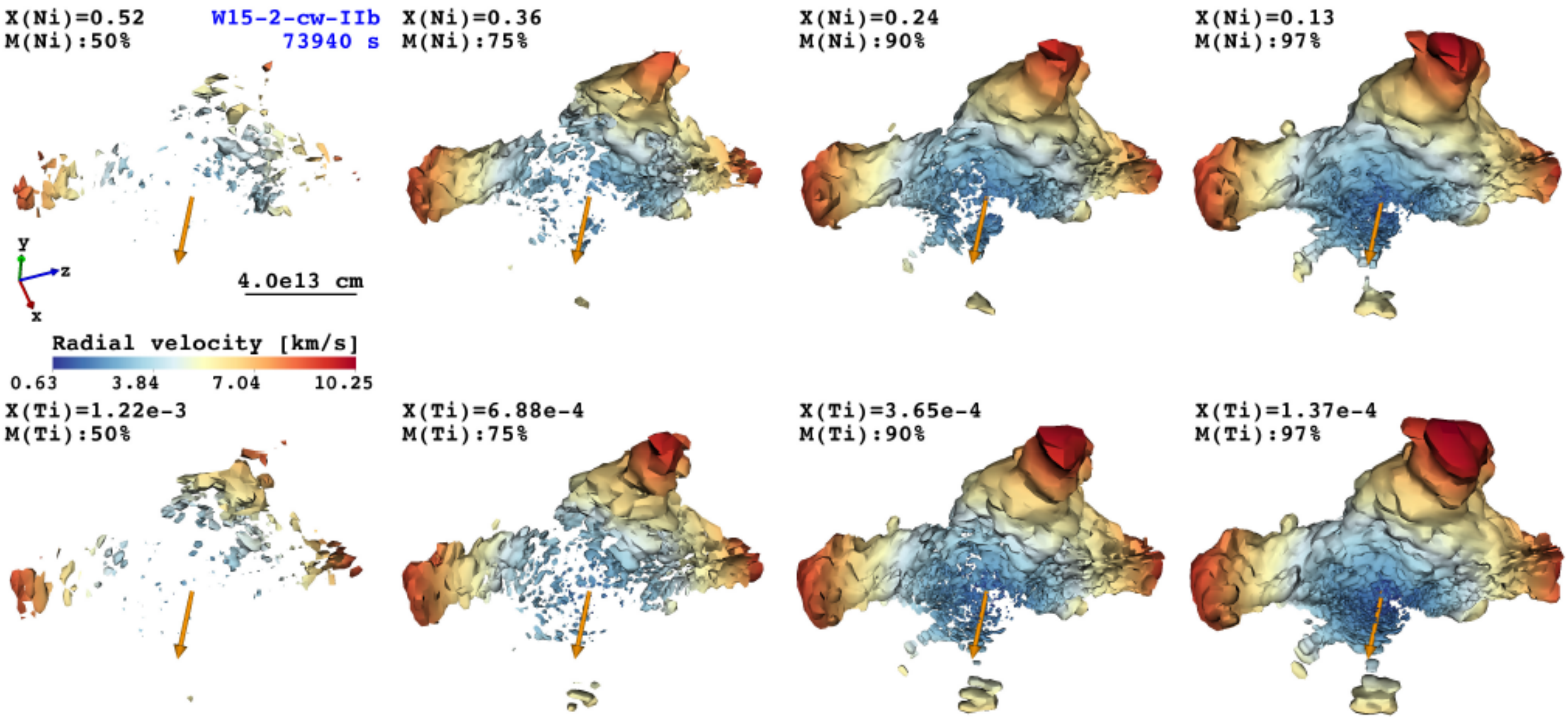


Grefenstette+2017



Observations versus Models

- Cas A ^{44}Ti ejecta morphology resembles simulation outcomes!
  ☞ Wongwatharanat+2017

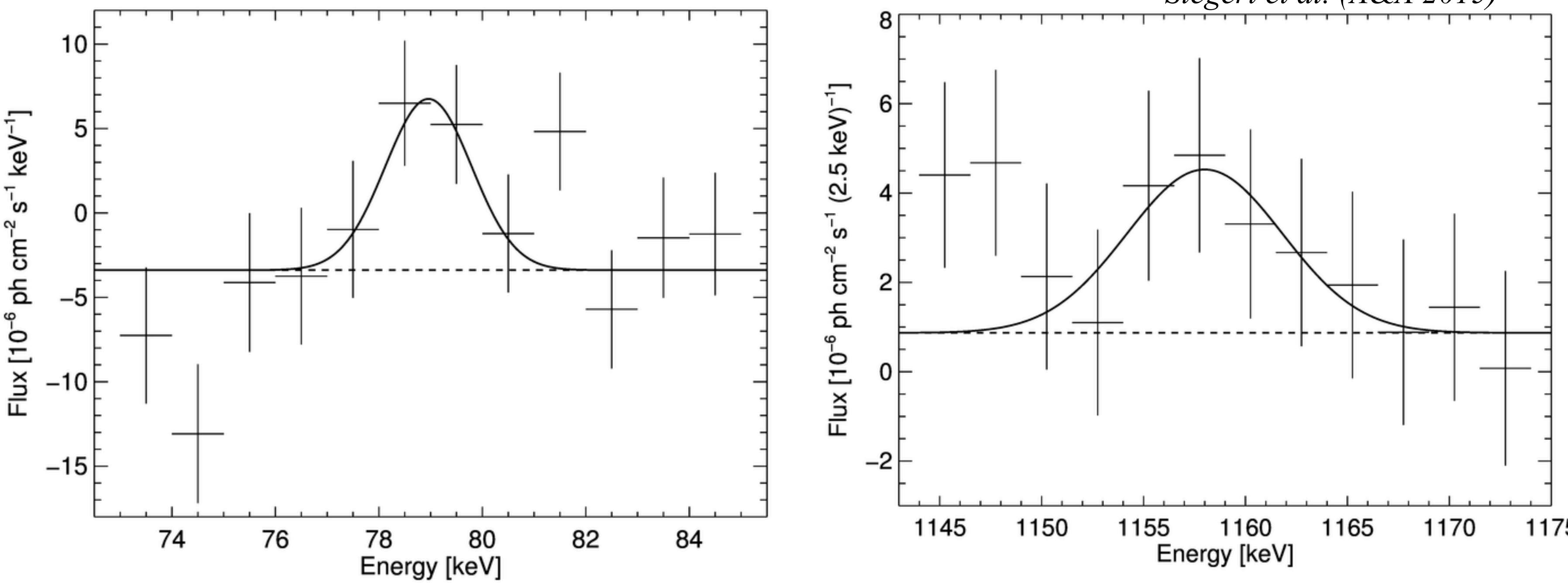


INTEGRAL/SPI Re-Analysis of Cas A for ^{44}Ti

Using cumulative data from >12 years,
and a new instrumental-background treatment

78 keV and 1157 keV line, seen with same instrument

Siegert et al. (A&A 2015)

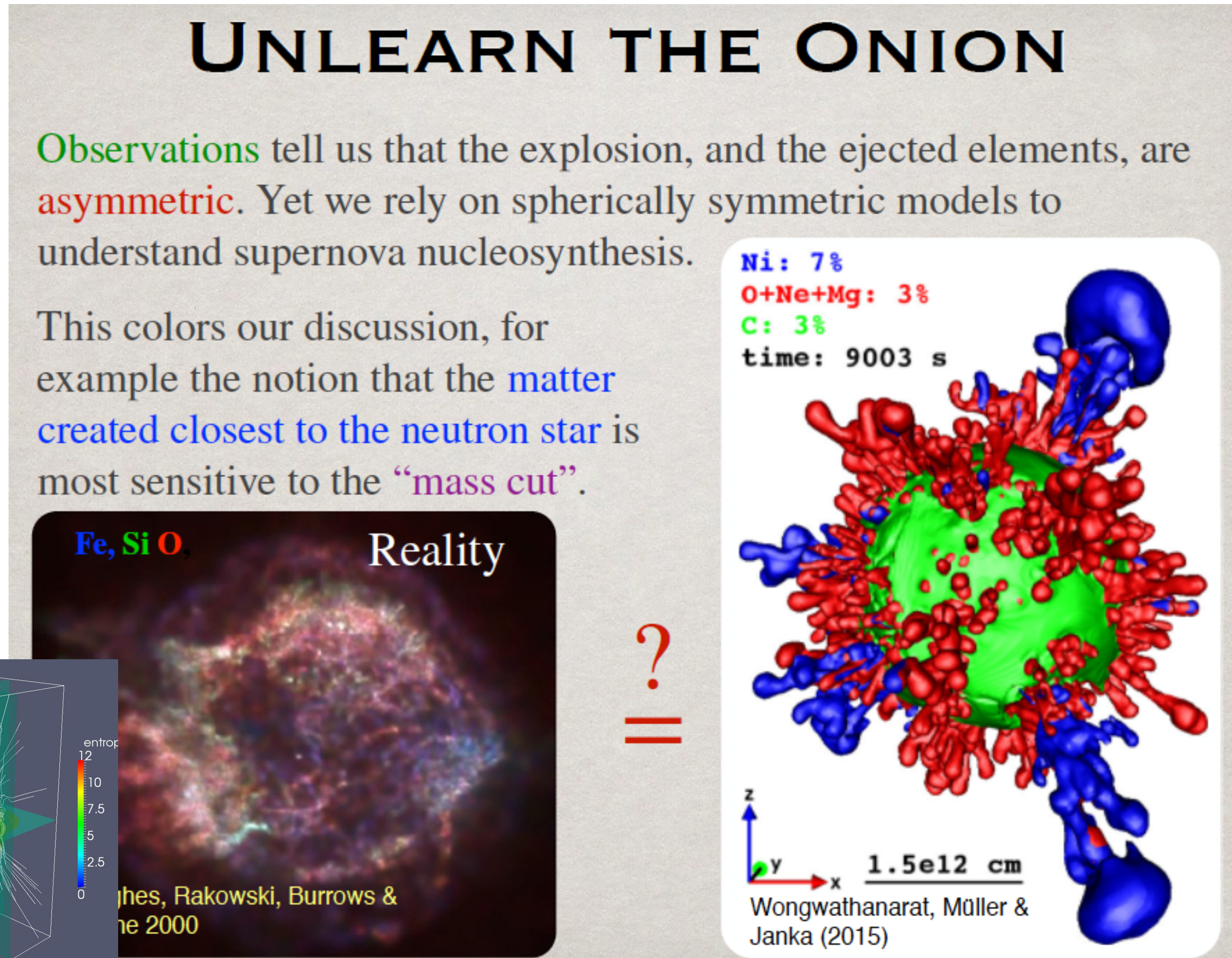


- ☆ Doppler broadening: 4300±1600 / 2200±1600 km s^{-1} (78, 1157 keV)
- ☆ ^{44}Ti mass = (1.29 ± 0.15) 10^{-4} M$_\odot$ (78 keV line only)
- ☆ ^{44}Ti mass = (2.72 ± 0.43) 10^{-4} M$_\odot$ (1.157 MeV line only)
- ☆

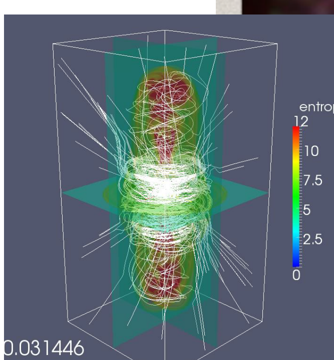
Core Collapse Supernovae

NIC 2018

- 3D effects are crucial (← ^{44}Ti X/gamma rays!)



- + rare variants!



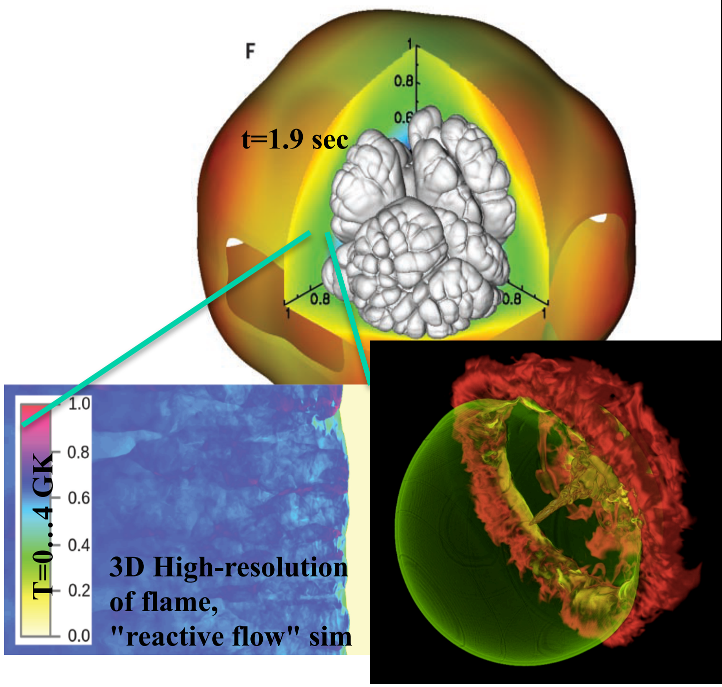
How we understand supernovae of type Ia

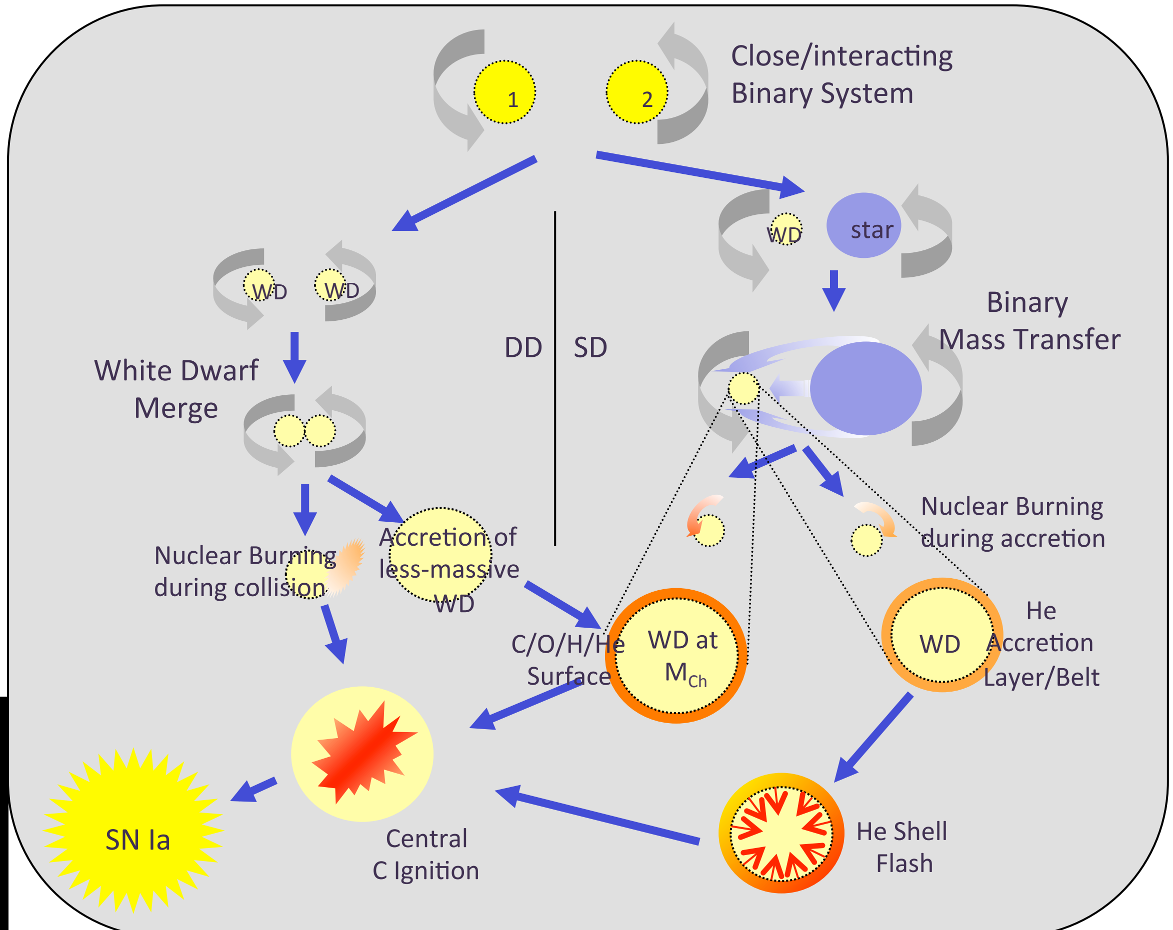
☆ Consensus:
Explosion of a CO WD (C fusion)

☆ Issues:

Ignition

Flame propagation

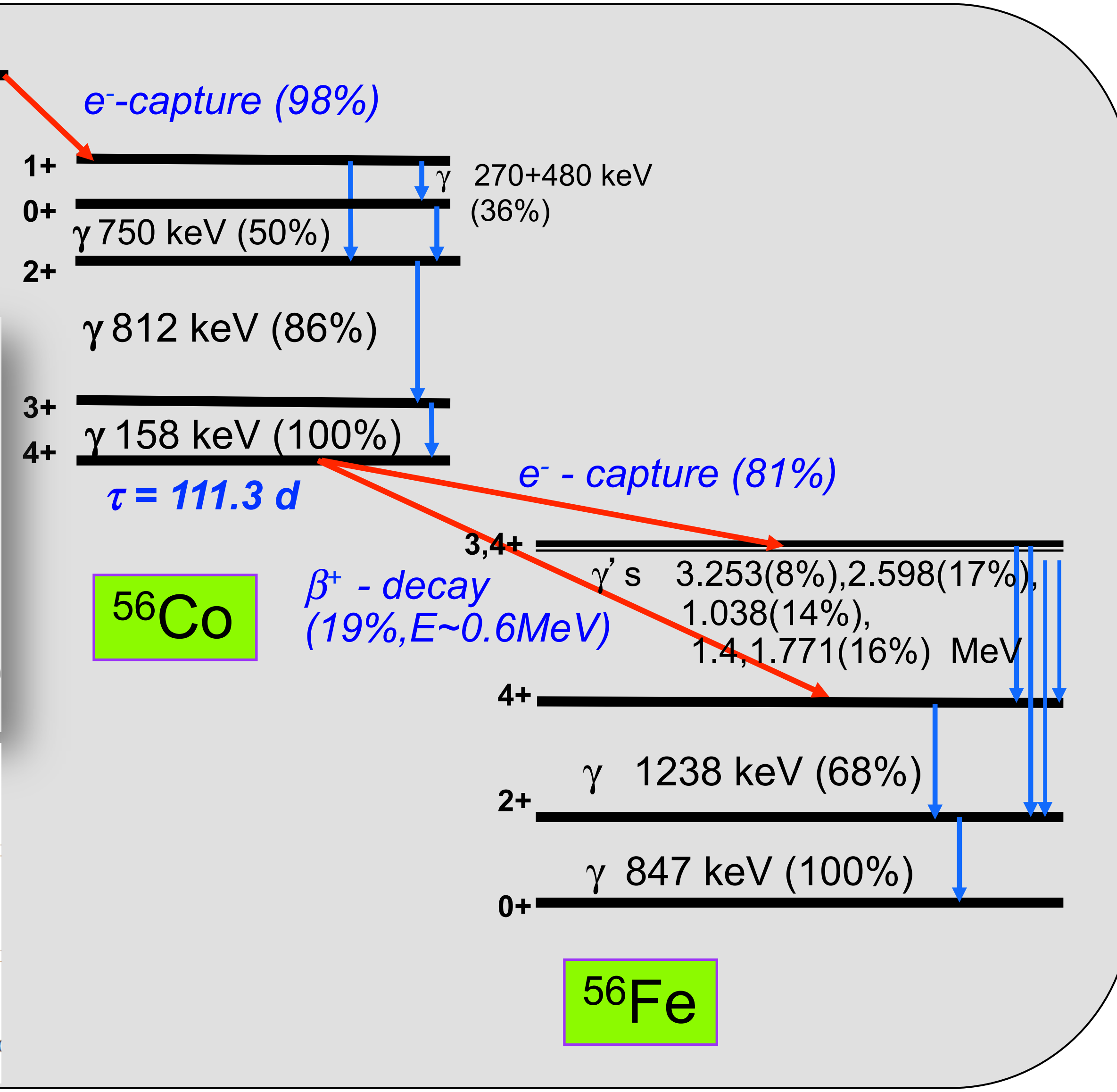


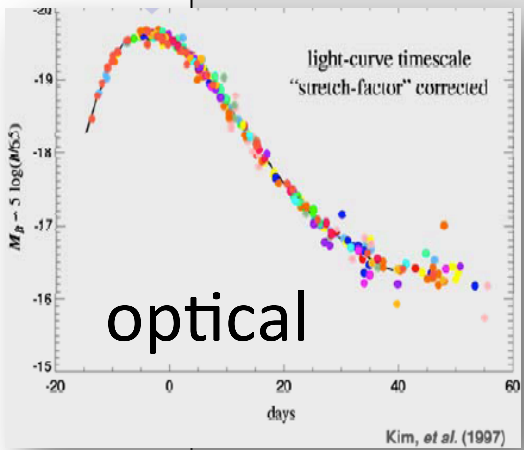


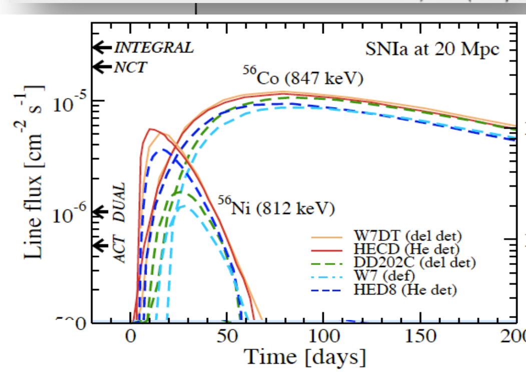
☞ ??

^{56}Ni padioactivity → γ-Rays, e^{+} → leakage/deposit

SN Ia

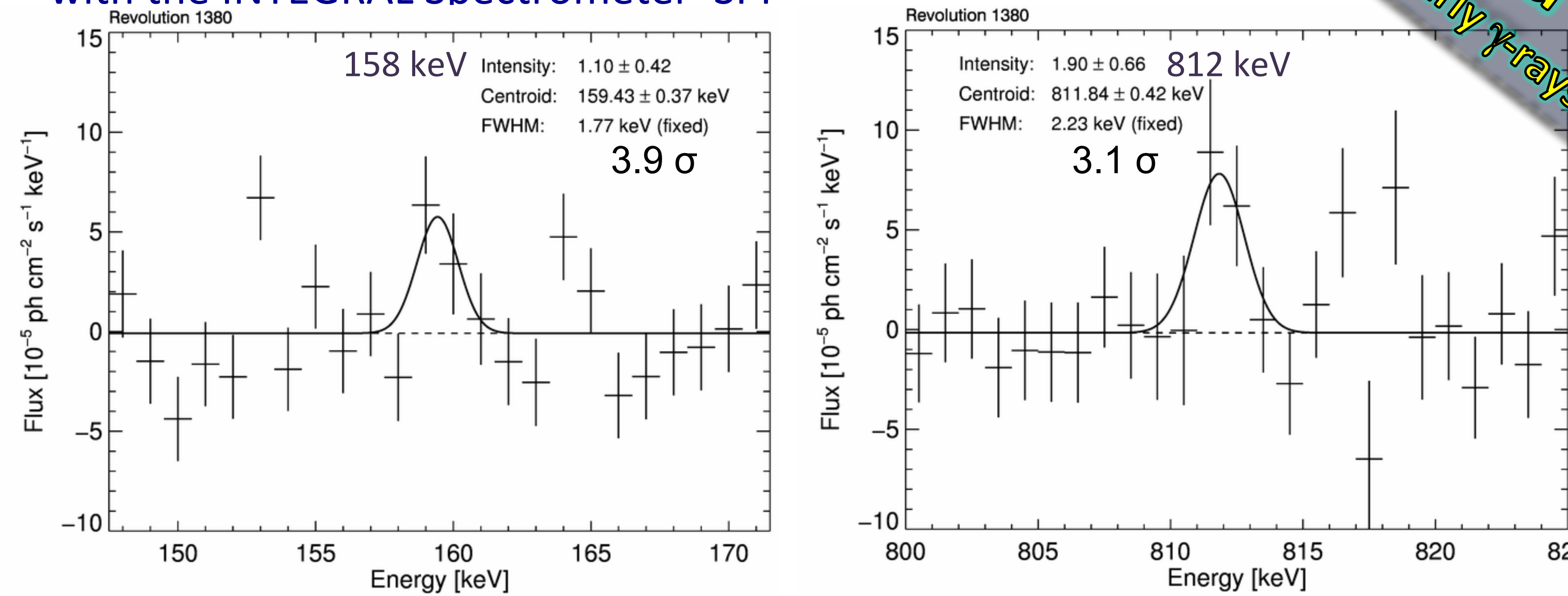






SN2014J: Early ^{56}Ni

- Spectra from the SN position
  - ☆ Clear detections of the two strongest lines expected from ^{56}Ni with the INTEGRAL Spectrometer 'SPI'

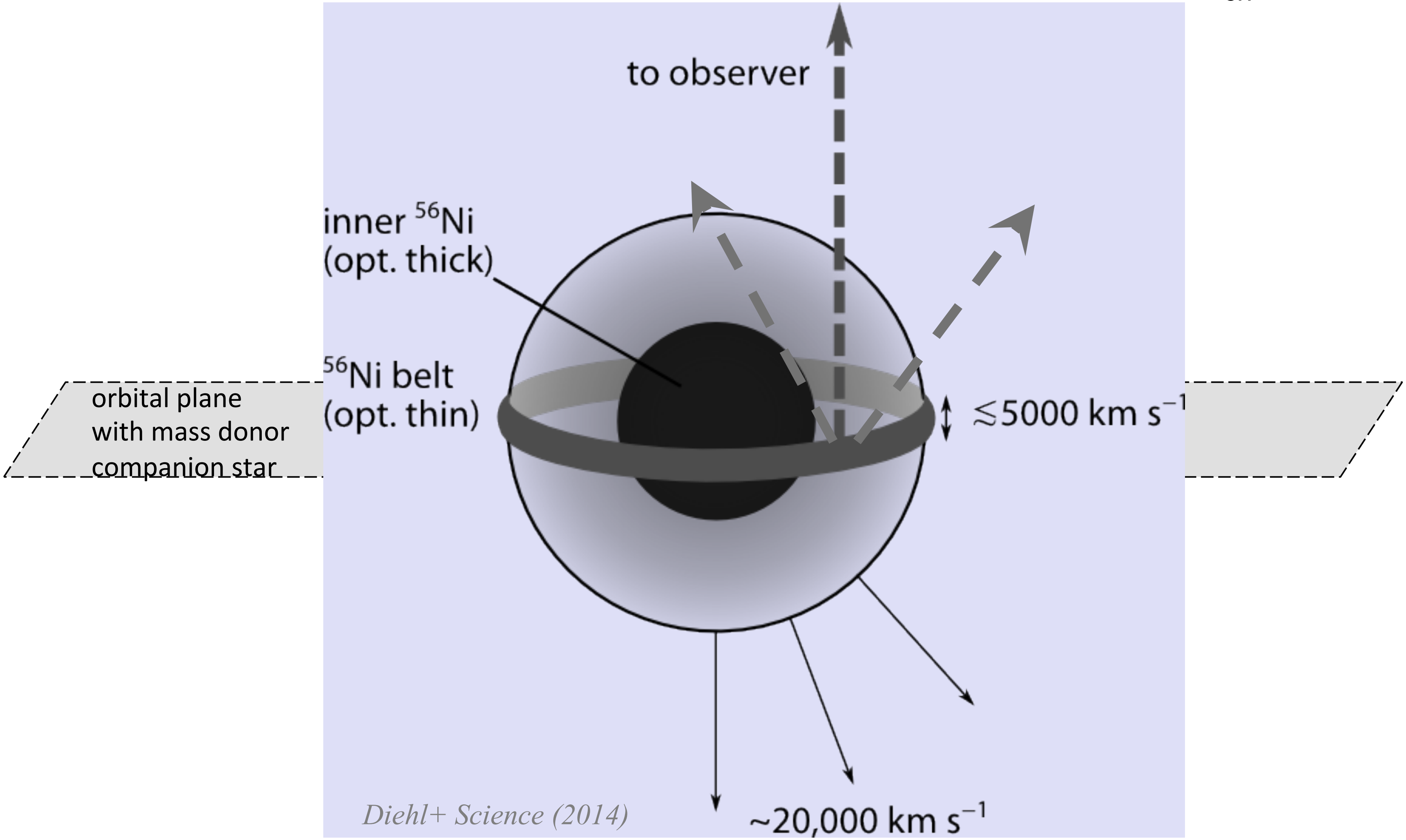


  - ☆ Intensities:
    (1.14 ±0.43) 10^{-4} ph cm^{-2} s^{-1} (158 keV line)
    and (1.91 ±0.67) 10^{-4} ph cm^{-2} s^{-1} (812 keV line)
  - ☆ ^{56}Ni mass estimate (backscaled to explosion): ~0.06 $M_{\odot}$

SN2014J: An unusual (triggered) explosion?

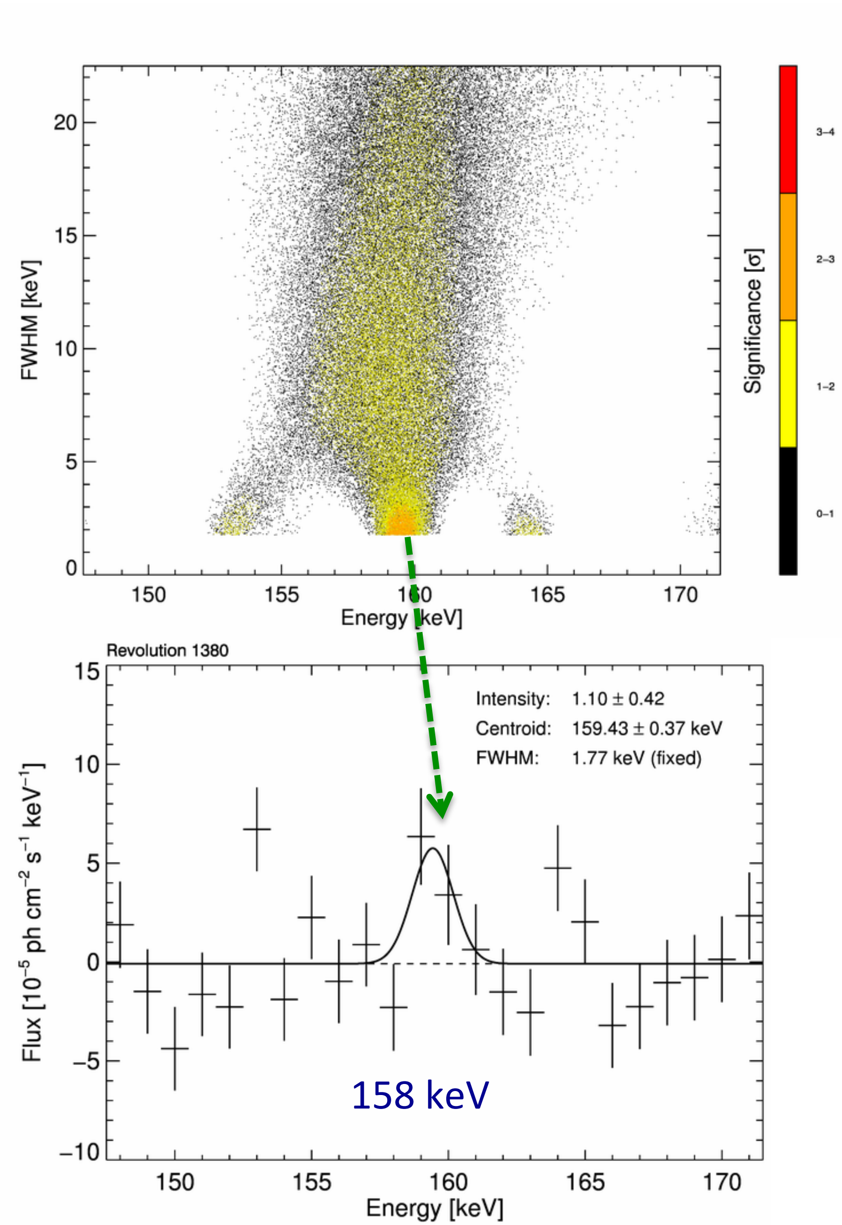
Possible scenario:

A belt of He accreted from the companion star → initial He explosion, triggering the SNIa explosion of the CO white dwarf ($M<M_{ch}$)



Diehl+ Science (2014)

Line Uncertainties: Search and method biases



- Random Search: Fit a Line with (Centroid,Intensity, Width), → significances (color)

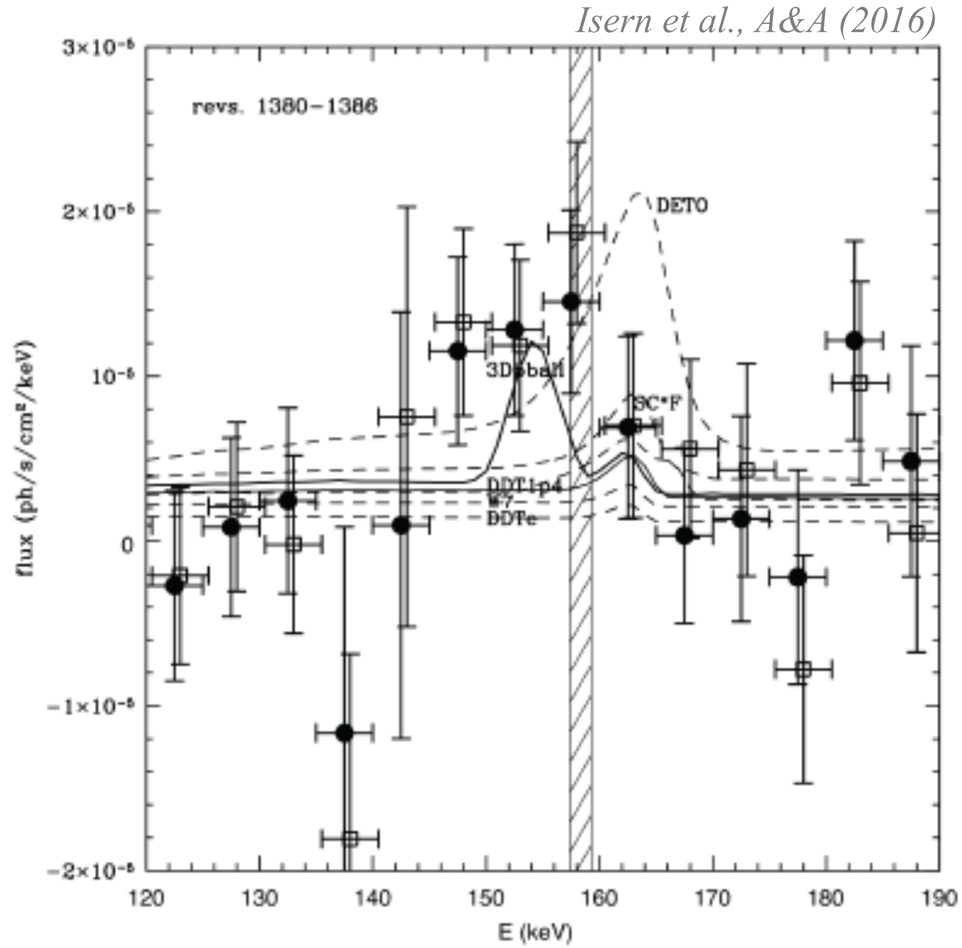
☞Narrow line, ~unshifted as most-likely solution

SN2014J: Early ^{56}Ni (τ~8.8d)

... and also an underlying broad line from early ^{56}Ni?

- ☆ Detection of ~158 keV emission also in broad-bin analysis
- ☆ An underlying broad, red-shifted line as well??
- ☆ ^{56}Ni mass estimate (backscaled

Isern et al., A&A (2016)



SN2014J data Jan – Jun 2014: 847 keV ^{56}Co line

☆ smooth(??) brightness evolution?

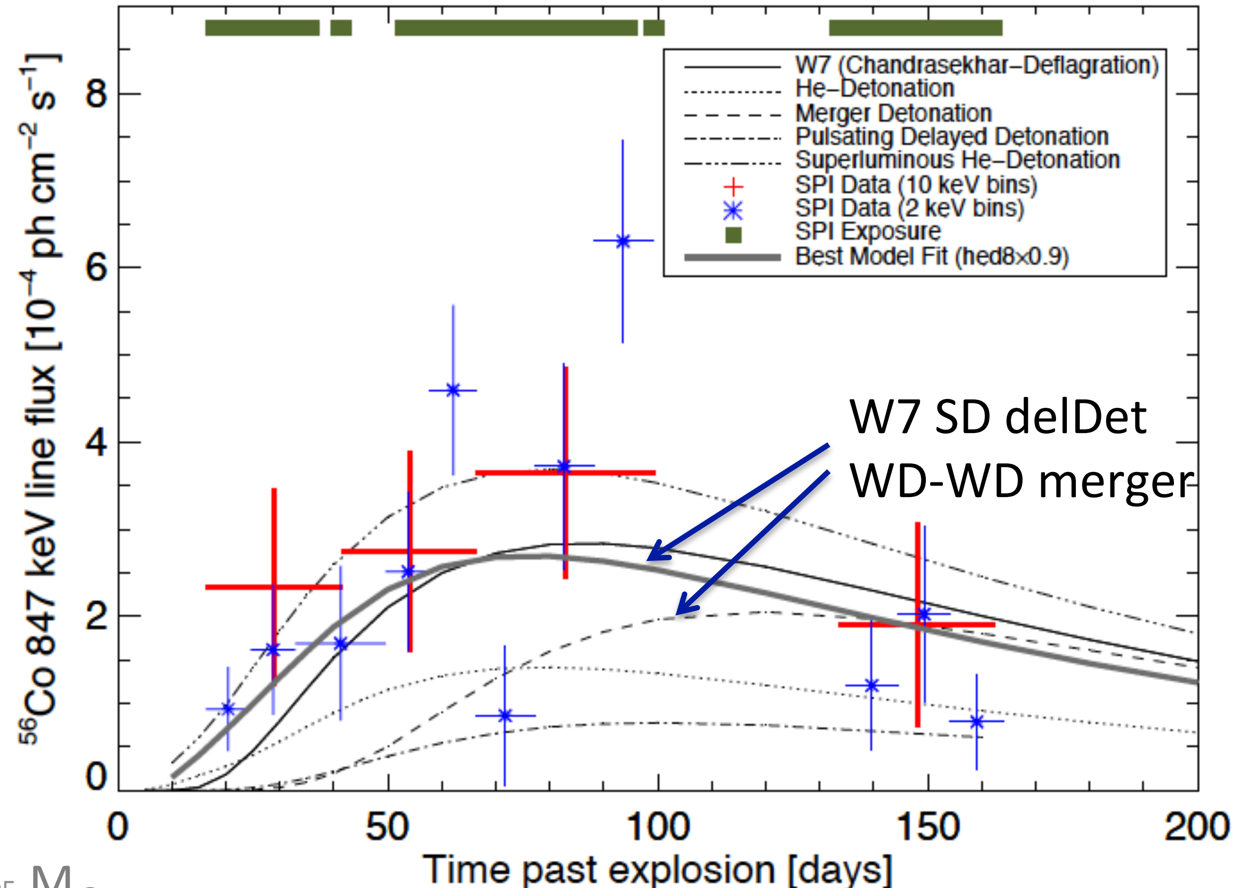
→ Compare high/low res data to models

☆ ^{56}Ni mass: 0.49 +/-0.09 $M_\odot$

(cmp from bol. Light → 0.42 +/-0.05 $M_\odot$

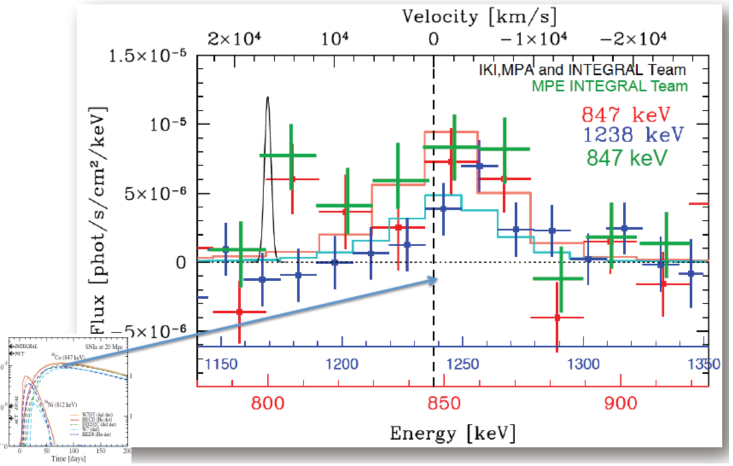
from models → 0.5 +/-0.3 $M_\odot$

☞ *Diehl et al., A&A 2015*



SN2014J data Jan – Jun 2014: ^{56}Co lines

- ☆ Doppler broadened ✓



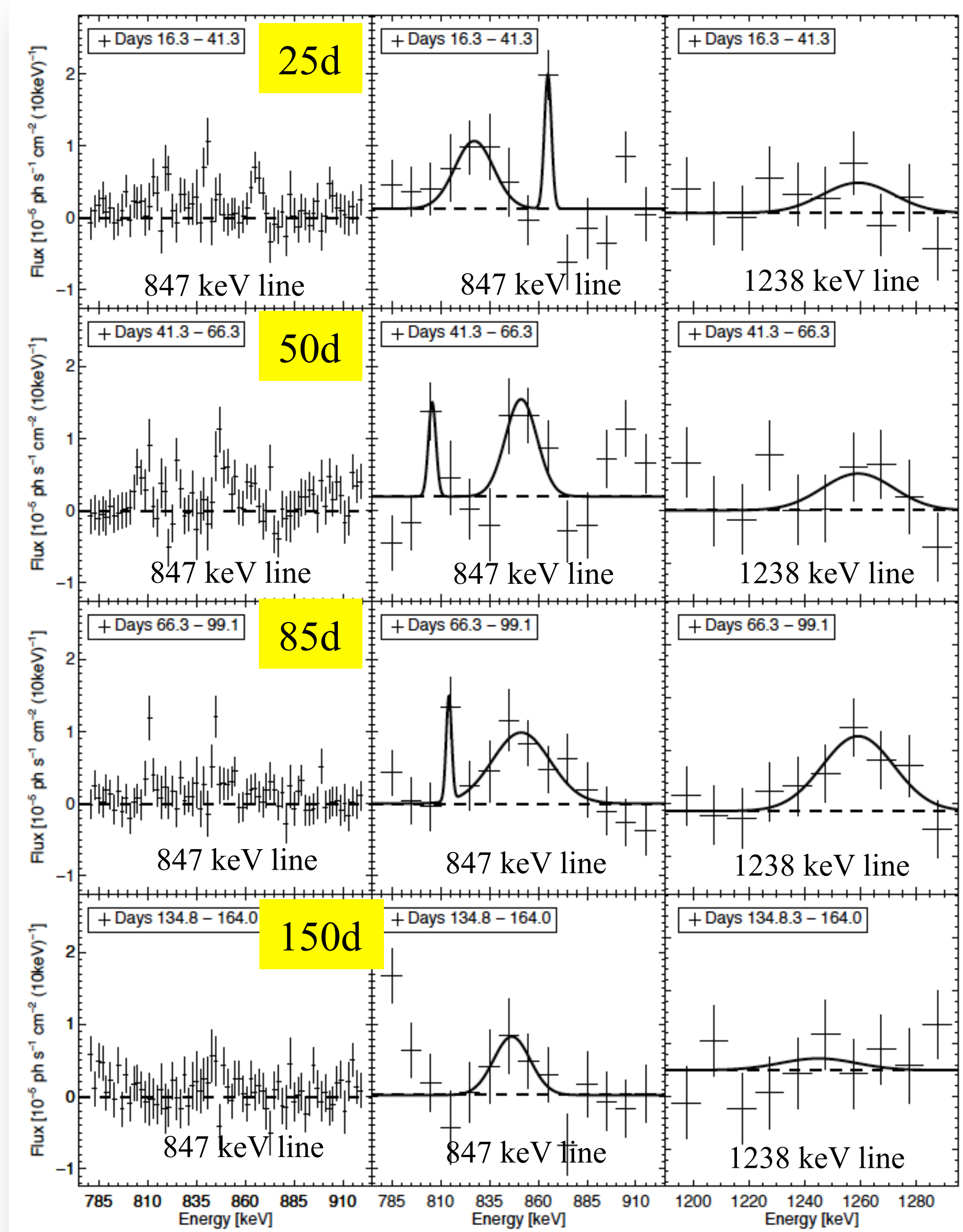
- ☆ Coarse & fine spectral binning

→ Observe a structured and evolving spectrum

– expected:
gradual appearance of broadened ^{56}Co lines

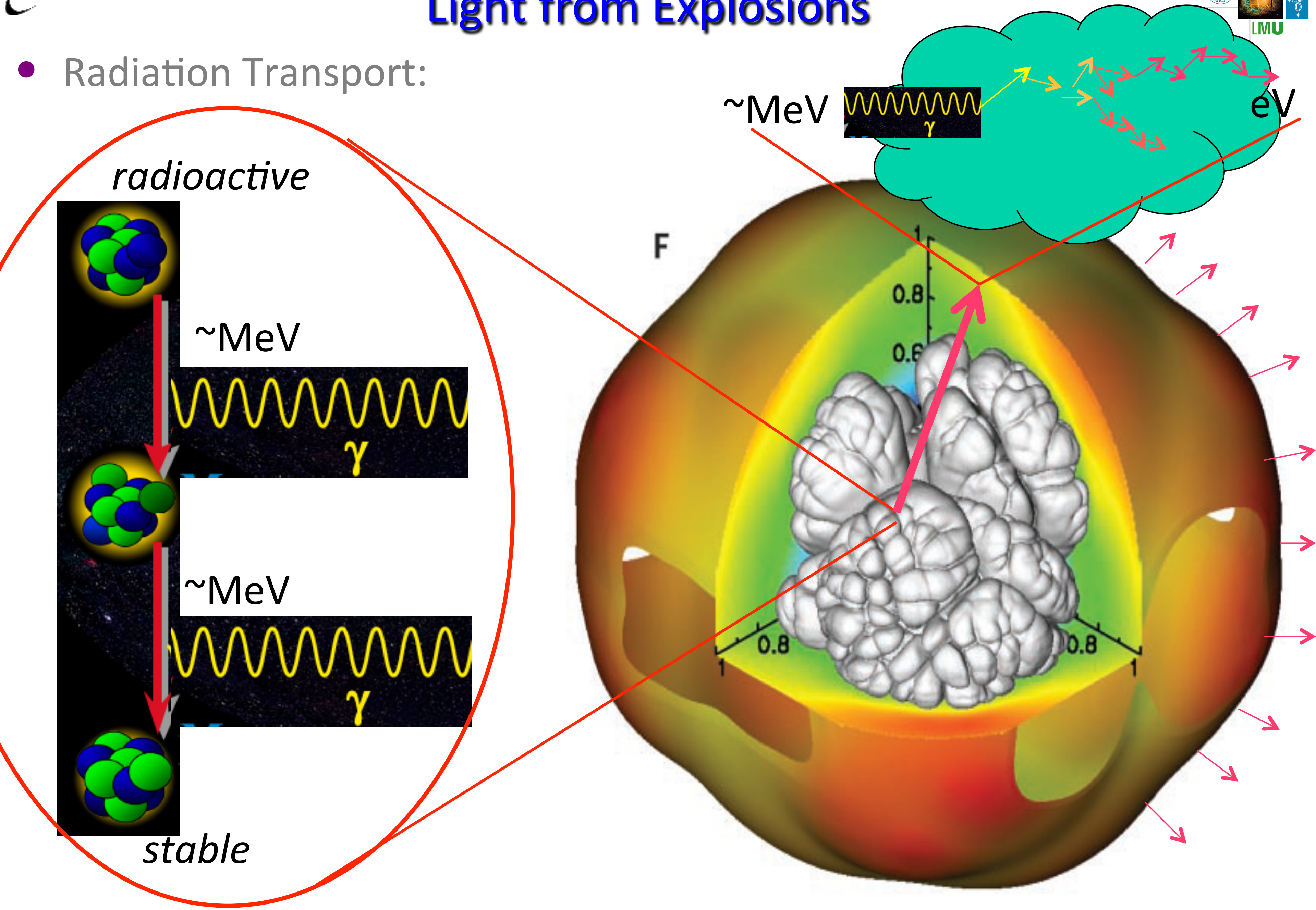
☞ *Diehl et al., A&A (2015)*

- ☆ ***How an envelope becomes transparent after an explosion***



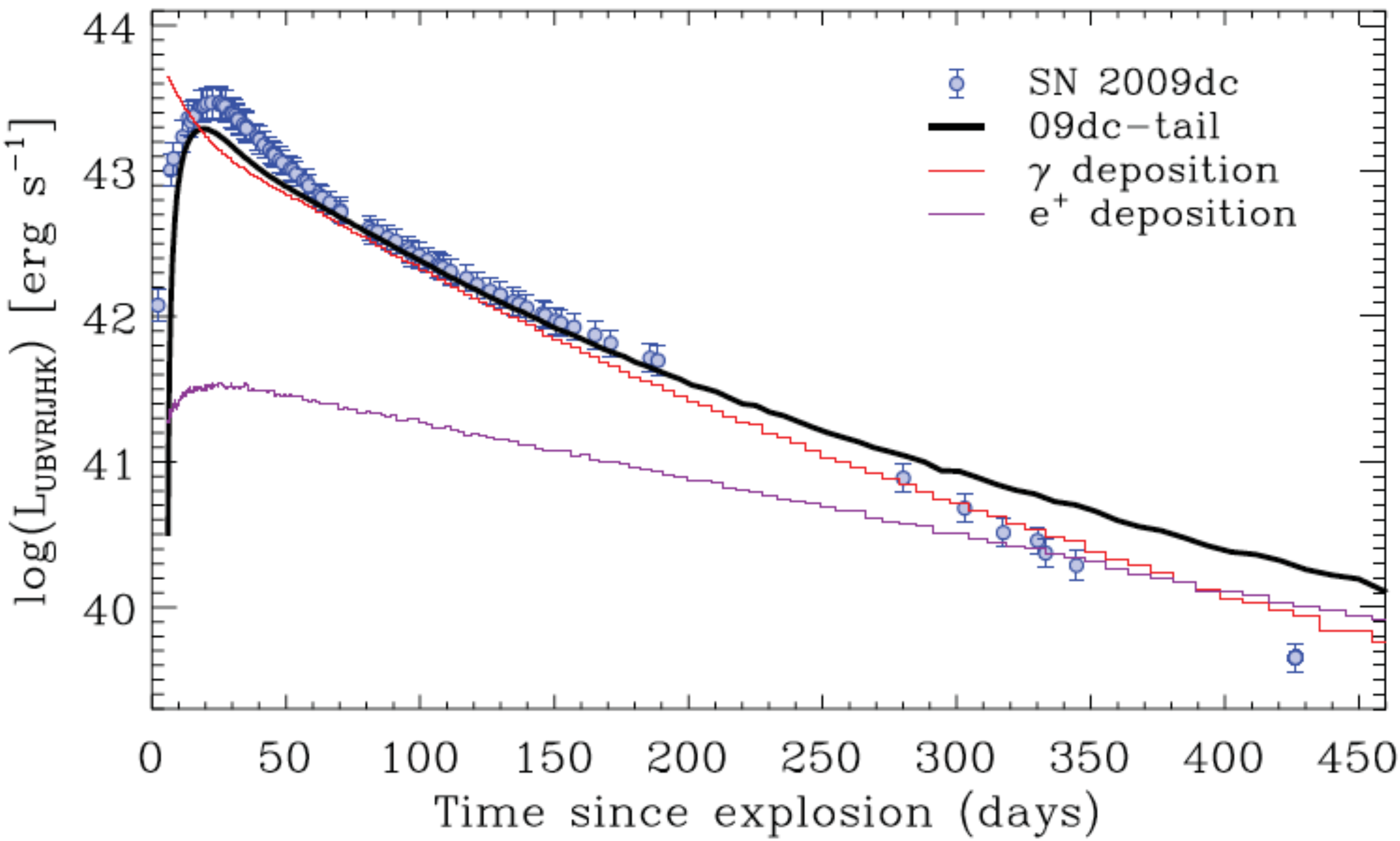
Light from Explosions

- Radiation Transport:



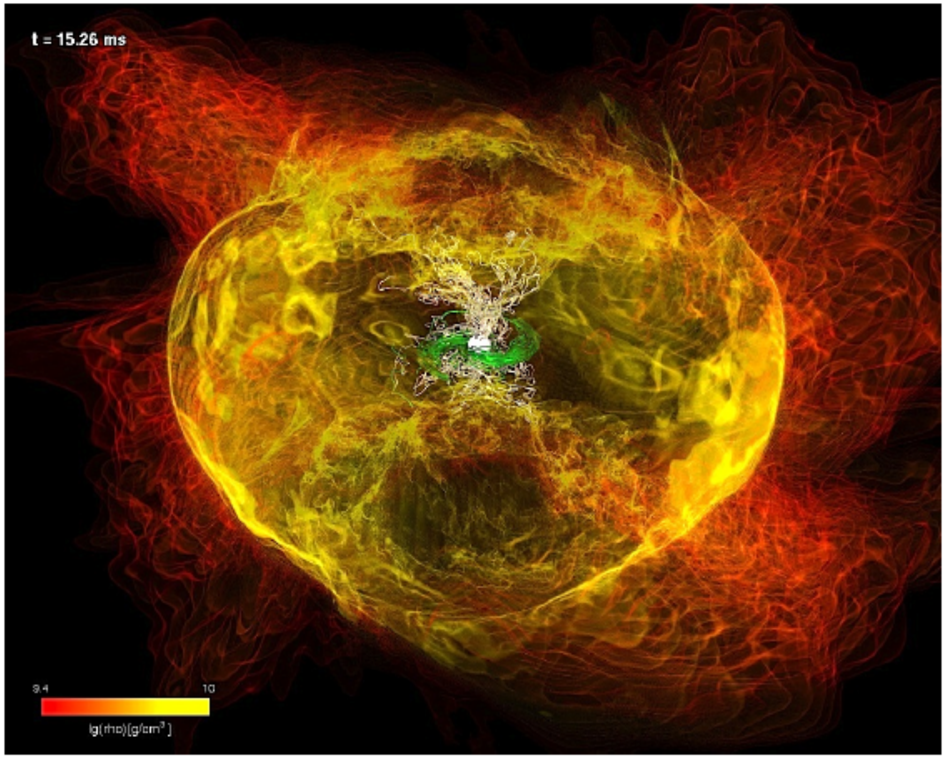
Deposition of Radioactivity in SNIa

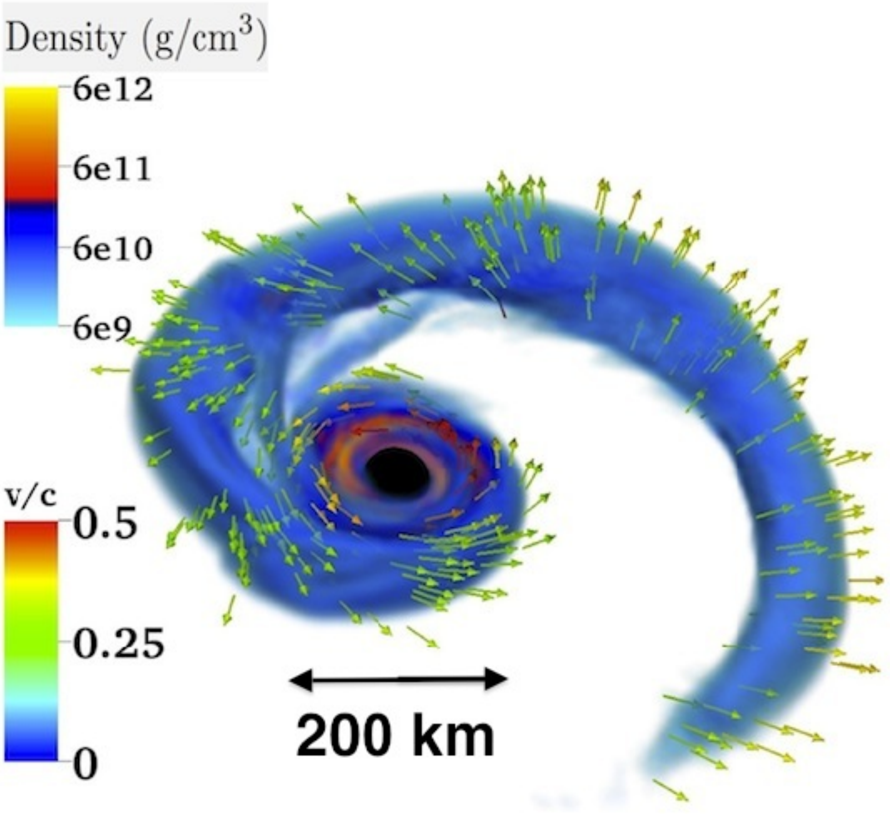
- Radiation transport:
  - ☞ Primary gamma-rays and positrons → UVOIR Light Curve
    - – example: DD/merger; Taubenberger et al. 2013



Post-merger dynamics

disruption of less-massive neutron star → ejection, nuclear reactions



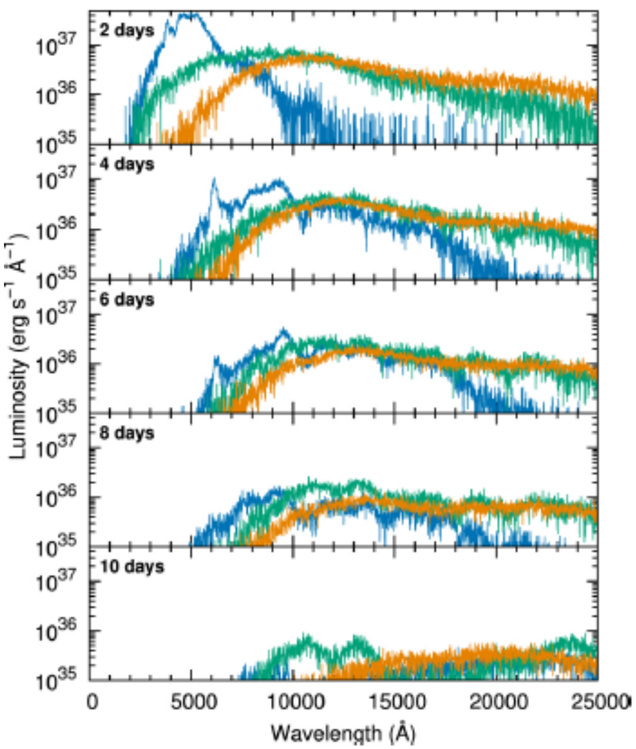


Fernández & Metzger 2016 from Rezolla+ 2011, and Fouchart+ 2014

Emission from a neutron star merger

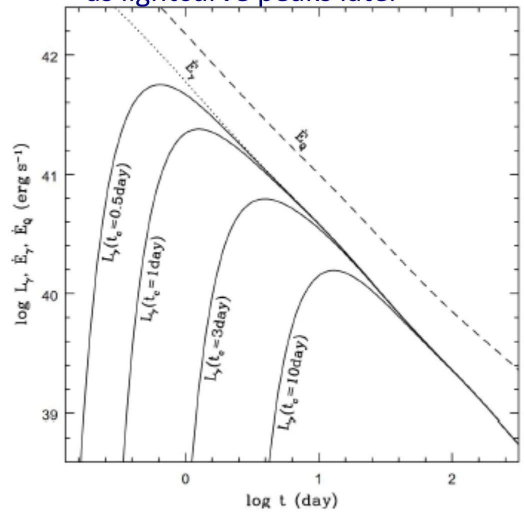
- Radioactivity deposits energy in ejecta components
- Gamma rays leak out

Evolution of low-energy emission (IR)

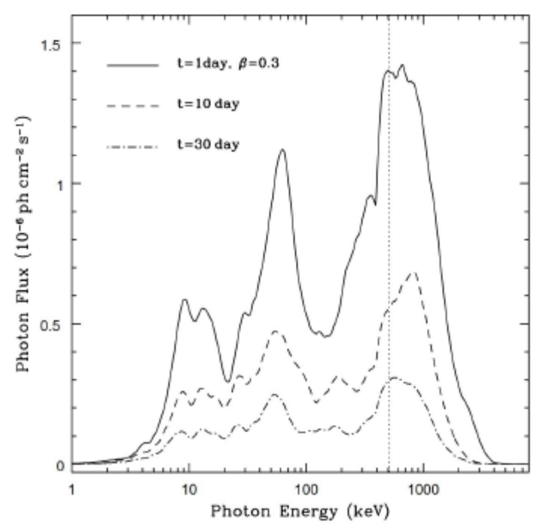


Gamma-ray emission

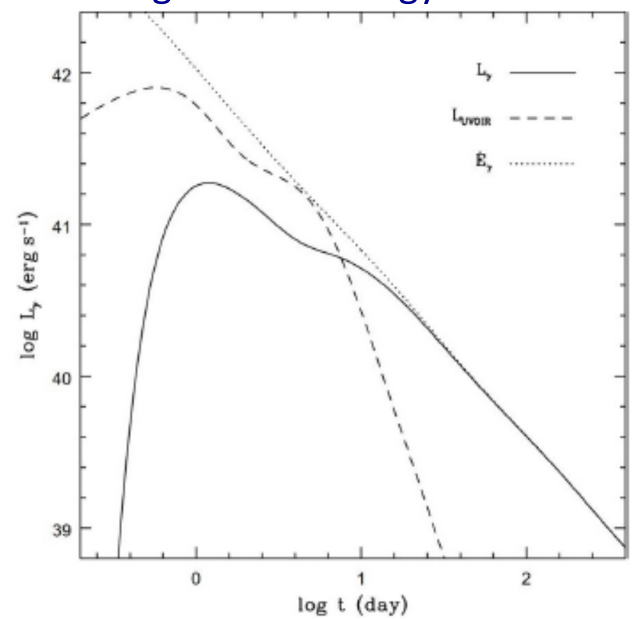
as lightcurve peaks later



Energy spectrum



→ Evolution of high & low-energy emission

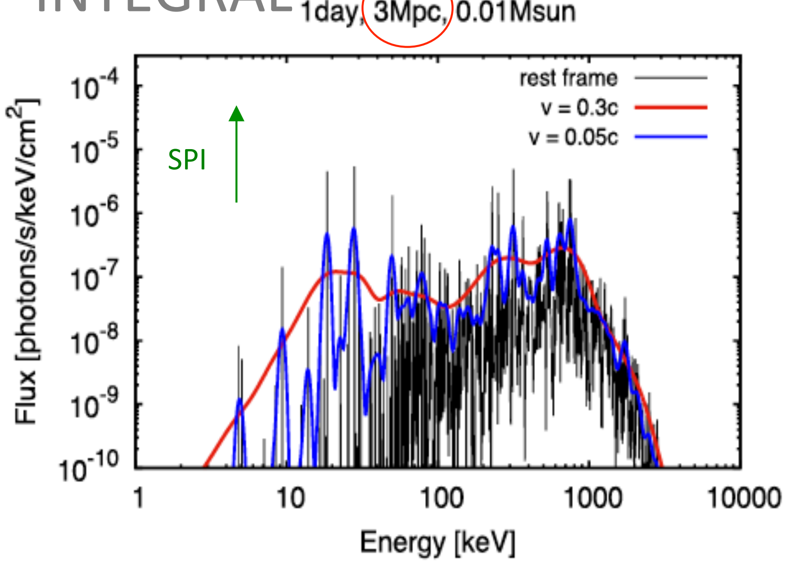


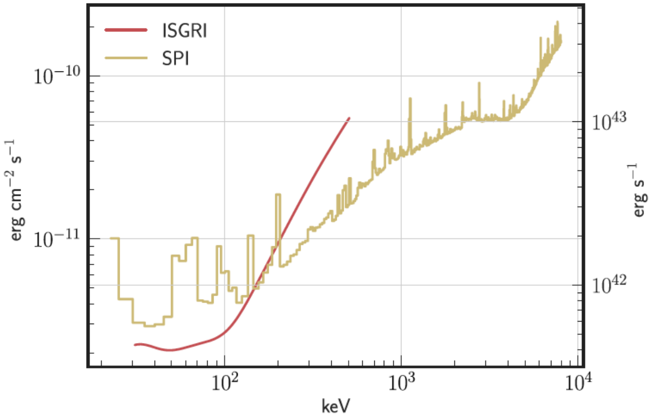
γ-ray line measurements of GW170817?

GW170817 is too distant!

Hotokezaka+ 2016

INTEGRAL

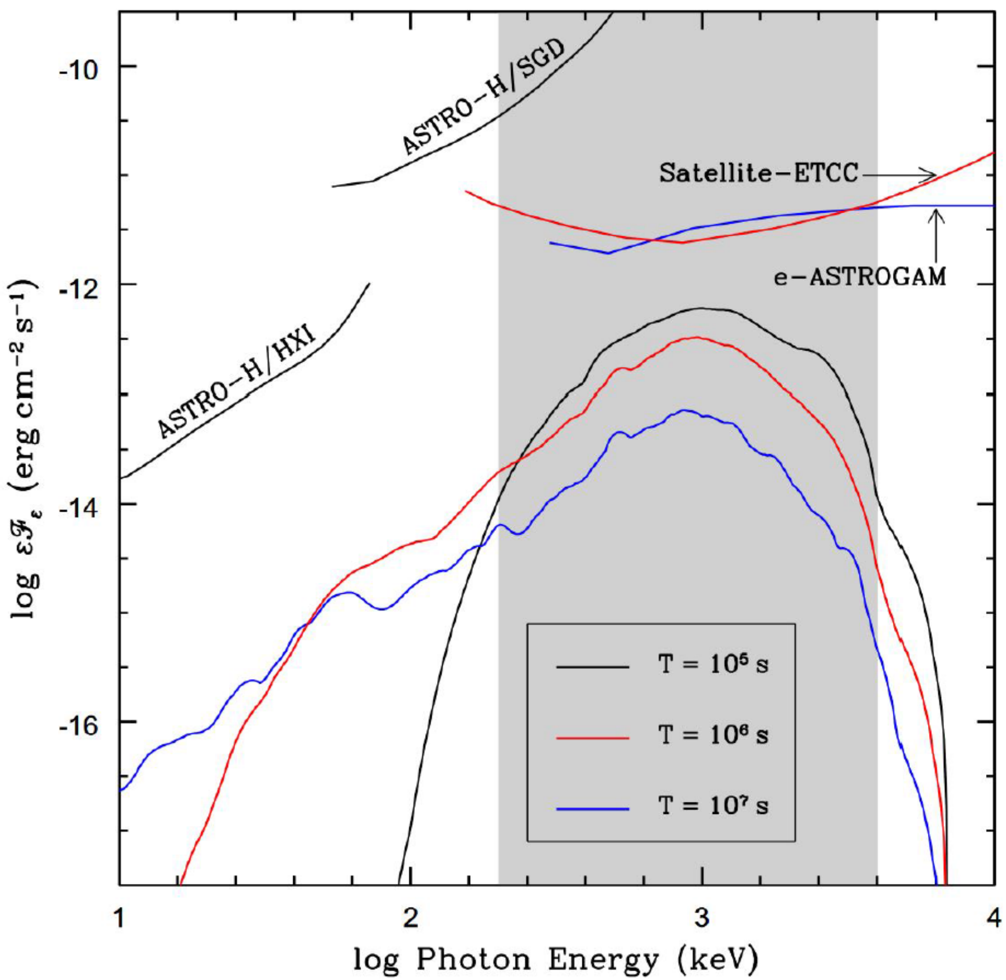




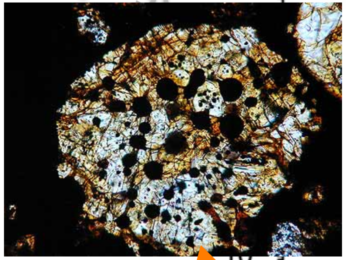
Savchenko et al. 2017

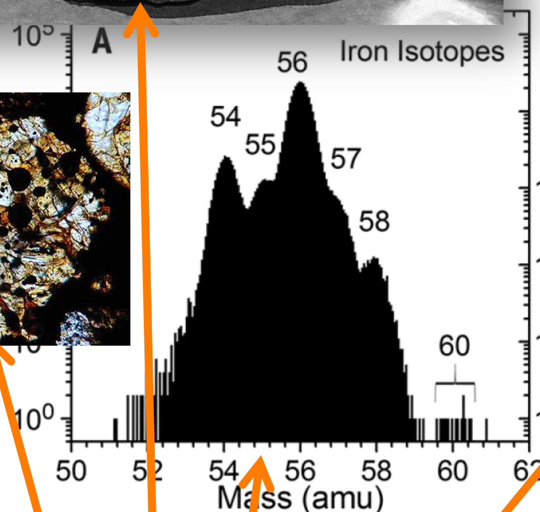
other instruments

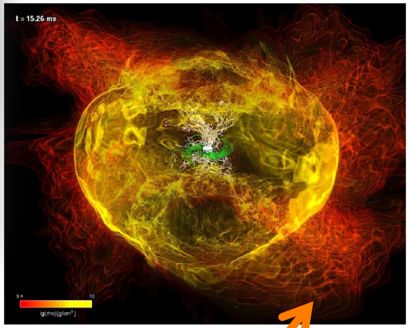
Li+ 2018

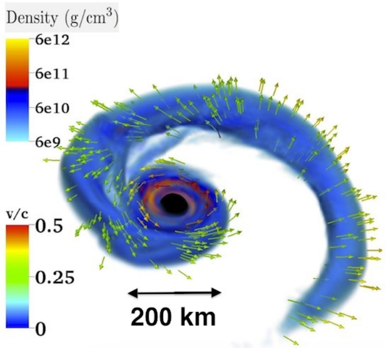


"Multi Messenger Astrophysics"









- St
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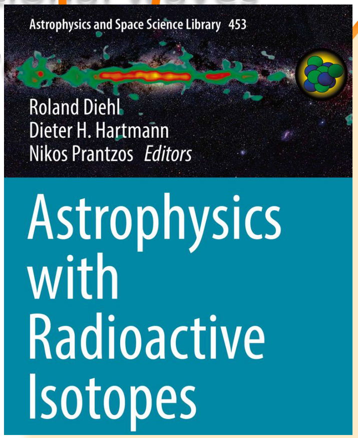
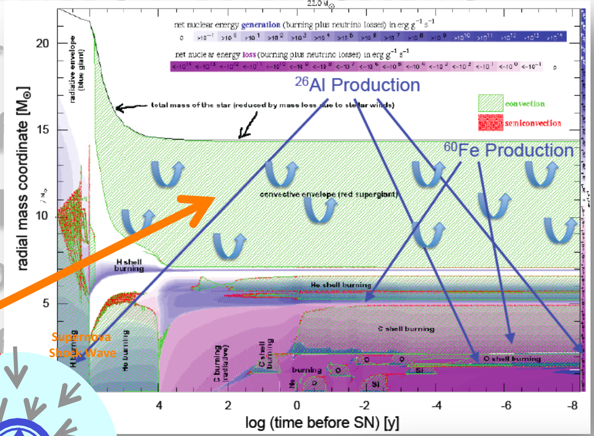
- Gravitational waves
- γ rays fr
- ...

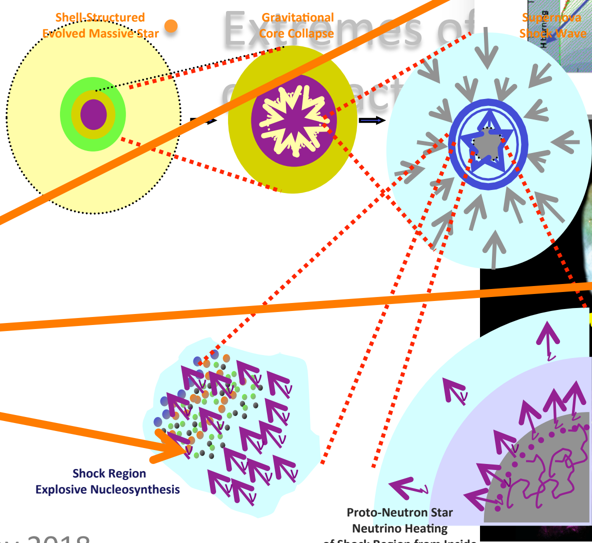
particles
others),
over local scales (→ solar system)

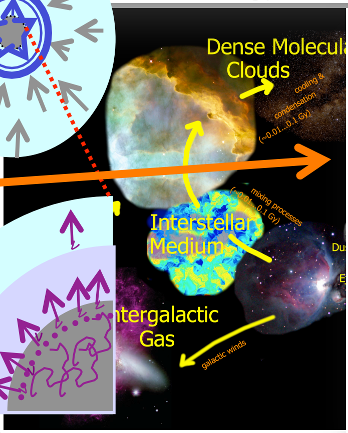
- Nuclear en
- Structure of
- Cosmic expl and their co
- Extremes of

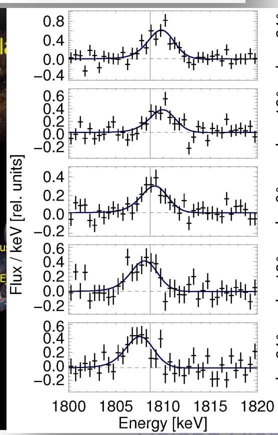
ms



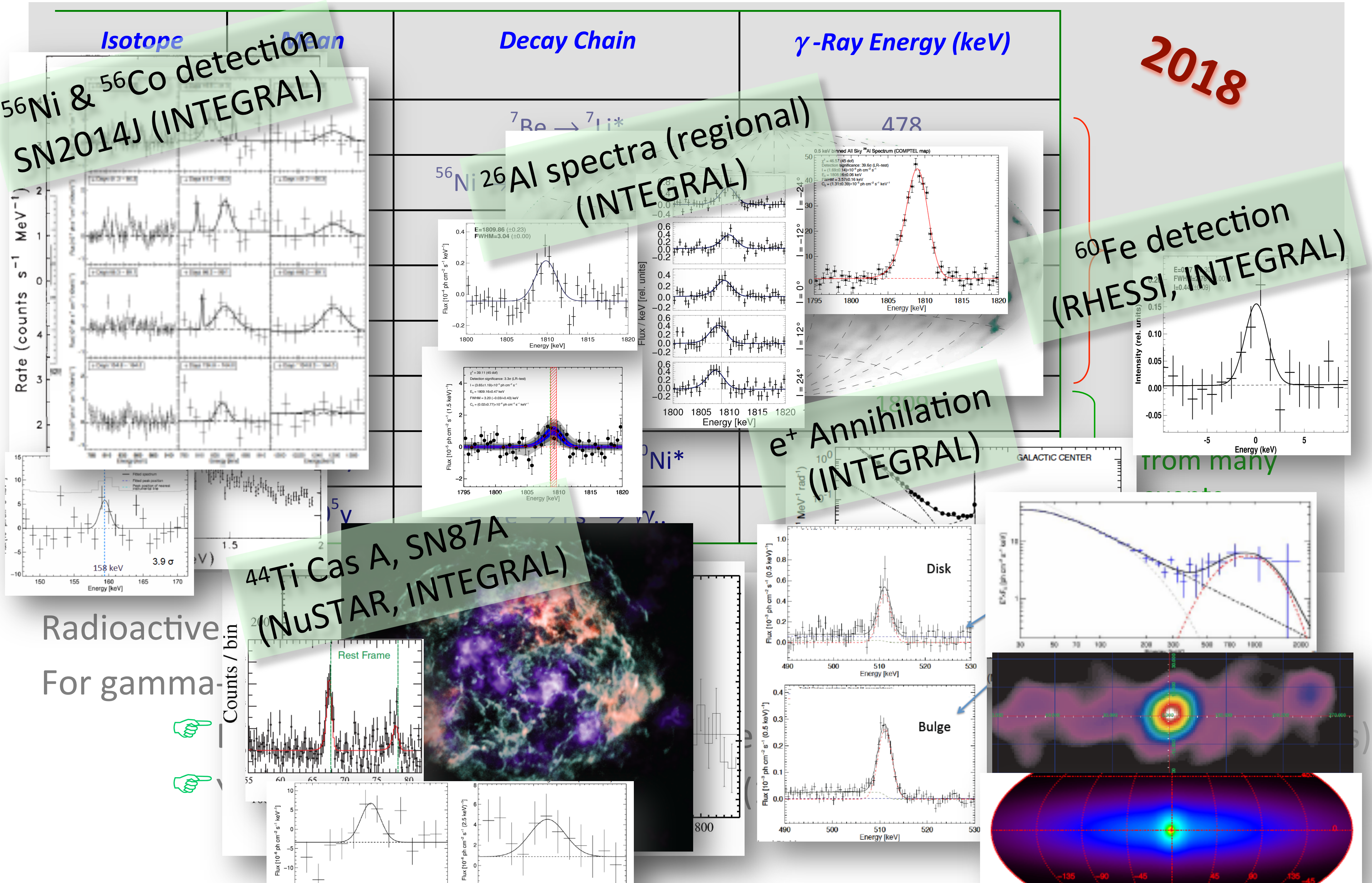






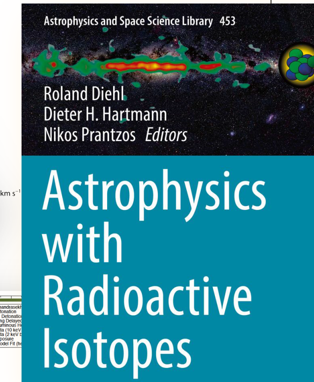


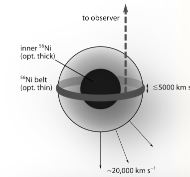
Nuclear Gamma-Ray Line Science Results

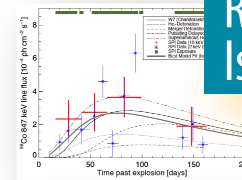


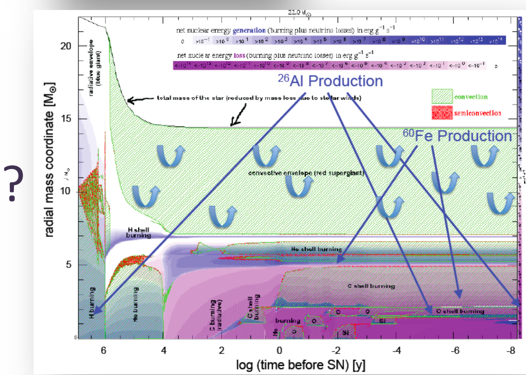
Cosmic Gamma Rays: Summary

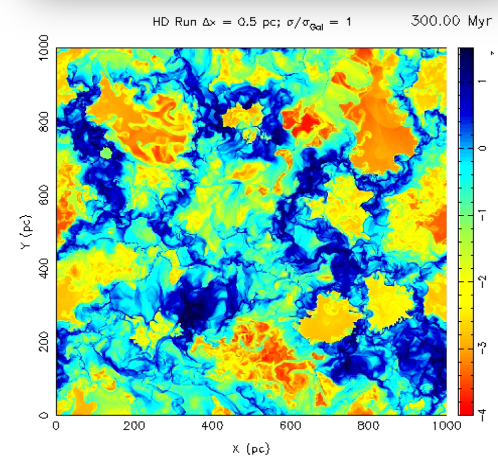
- ☆ γ-rays provide a unique / different view
  - Yield constraints for SNe and Novae, Independent of complexity from unfolding of the explosion
  - Radioactivity traces diluted ejecta at late phases
  - Nuclear de-excitation traces CRs, and ionised gas
- ☆ SNIa ^{56}Ni and how the explosion generates SN light
  - SN2014J reveals its ^{56}Ni,^{56}Co irregularly → 3D effects?
- ☆ ccSupernova ^{44}Ti demonstrates SN asymmetries
  - Only Some SN Eject ^{44}Ti, but then much, and clumpy
- ☆ Massive-star shell structure & evolution tests: ^{26}Al, ^{60}Fe
  - ^{26}Al as a tool: understand groups of massive stars (My
  - How much ^{60}Fe from n captures in C and He shells?
- ☆ ISM in the Galaxy: Role of superbubbles; e$^+$ sources
  - ^{26}Al spreads into large (super)bubbles
  - e$^+$ sources are a variety & puzzle; incl μQSOs



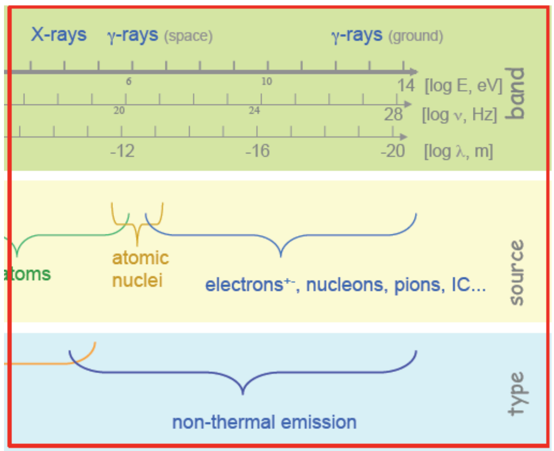




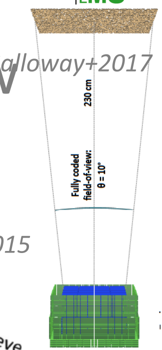


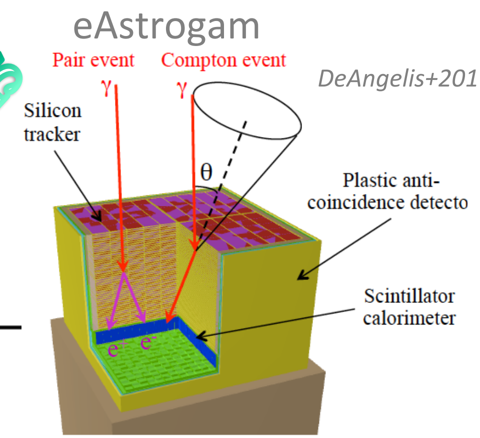


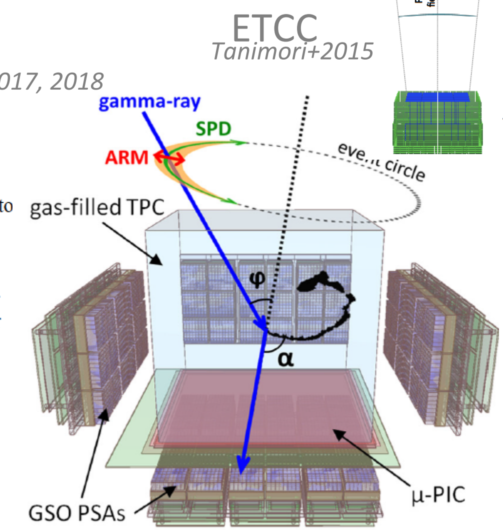
Perspectives: New/better observations?

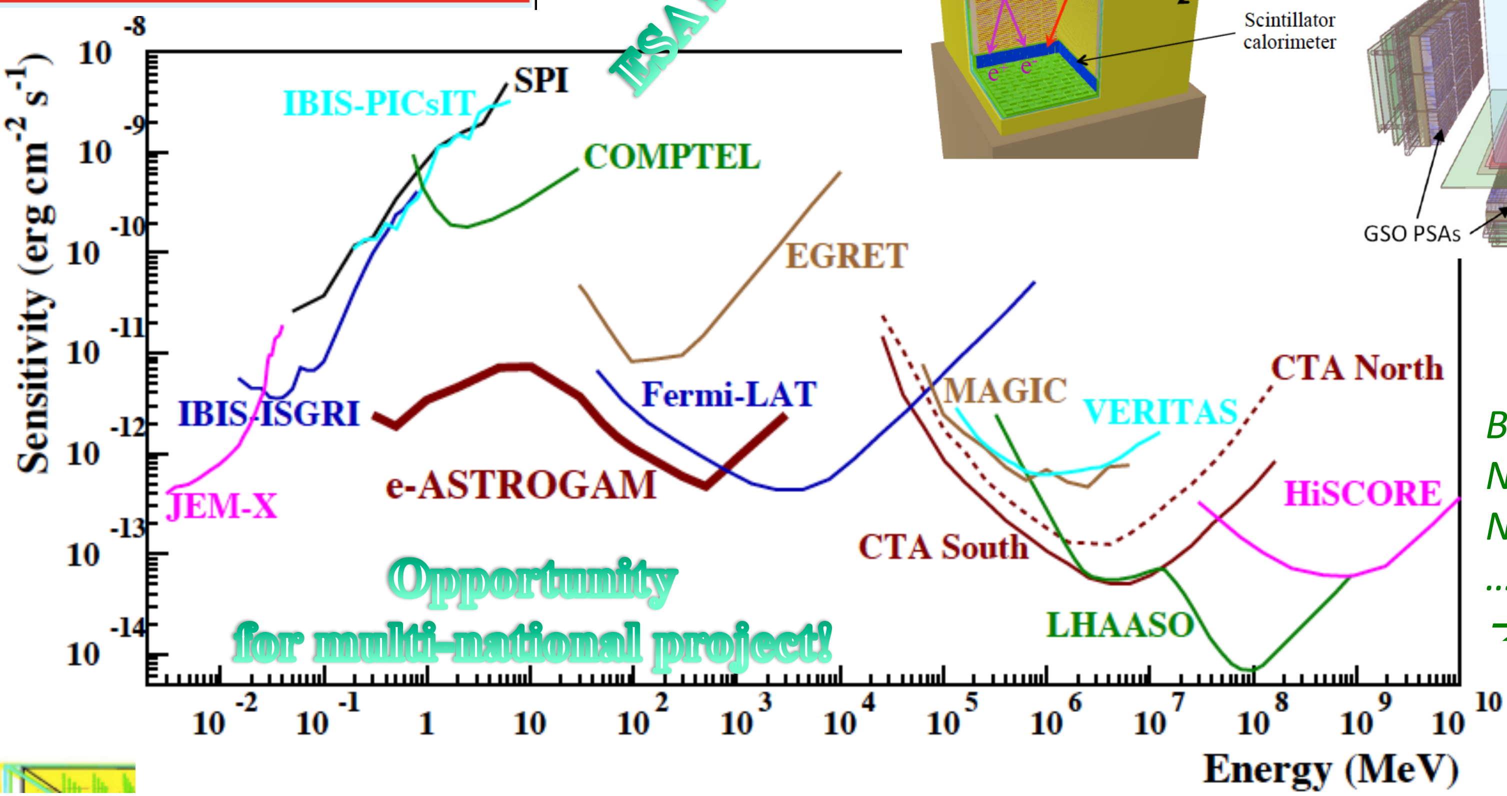


- We can do now >one o.o.m. better now
  - ☆ Compton Telescope most promising









But:
Not before >10 years
Not for narrow lines
…
→ Maintain INTEGRAL/SPI !!